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A Theory of Human Error

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Duane T. McRuer
Warren F. Clement
R. Wade Allen

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A Theory of Human Error

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ABSTRACT

Human error is a significant contributing factor in a very high proportion of civil transport, general aviation, and rotorcraft accidents. Finding ways to reduce the number and severity of human errors would thus appear to offer promise for a significant improvement in aviation safety. Human errors in aviation tend to be treated in terms of clinical and anecdotal descriptions, however, from which remedial measures are difficult to derive. Correction of the sources of human error requires that one attempt to reconstruct underlying and contributing causes of error from the circumstantial causes cited in official investigative reports. A comprehensive analytical theory of the cause-effect relationships governing propagation of human error is indispensable to a reconstruction of the underlying and contributing causes. This report presents a validated analytical theory of the input-output behavior of human operators involving manual control, communication, supervisory, and monitoring tasks which are relevant to aviation operations. This theory of behavior, both appropriate and inappropriate, provides an insightful basis for investigating, classifying, and quantifying the needed cause-effect relationships governing propagation of human error.

FOREWORD

This report was prepared under NASA Contract NAS2-10400 sponsored by the Man-Vehicle Systems Research Division of Life Sciences at Ames Research Center. The contract technical monitor was Dr. David C. Nagel, the Systems Technology, Inc., (STI) technical director was Mr. Duane T. McRuer, and the STI project engineer was Mr. Warren F. Clement. This report was prepared during the interval from November 1979 through April 1980.

The authors have endeavored to acknowledge by textual reference the specific contributions of the many other researchers which have helped to make this work possible. In addition the authors wish to thank the following individuals for their assistance in preparing this volume. The contract technical monitor for his constructive criticism and guidance and Sharon A. Duerksen, Kay J. Wade, and Charles W. Reaber of the STI staff for their help in publishing the volume itself.

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LIST OF ABBREVIATIONS

ATC	Air traffic control
ATCRBS	Air traffic control radar beacon system
CNI	Communications, navigation, and identification
DABS	Discrete address beacon system
DDC	Defense Documentation Center
ETABS	Electronic tabular display system
FAA	Federal Aviation Administration
IFR	Instrument flight rules
IMC	Instrument meteorological conditions
NASA	National Aeronautics and Space Administration
PML	Perceptual motor load
PPI	Plan position indicator
SID	Standard instrument departure
SOP	Successive organization of perception
STAR	Standard terminal arrival route
VFR	Visual flight rules
VMC	Visual meteorological conditions

SECTION I

INTRODUCTION

A. BACKGROUND AND PURPOSE

Findings by the Flight Safety Foundation, the National Transportation Safety Board, and others indicate that human error is at least a major contributing factor in a very high proportion (80 percent or more) of civil transport, general aviation, and rotorcraft accidents. Finding ways to reduce the number and severity of human errors would thus appear to offer great promise for a significant reduction in accidents and improvements in aviation safety.

The proportional involvement of human errors in aviation accidents has been relatively stable in spite of many changes in the Air Traffic Control System and typical cockpits. This does not mean, however, that an irriducible minimum has been reached. Instead, we appear to be on a plateau in understanding the quantitative details of just how the human elements contribute. To make a significant dent in error reduction requires a better appreciation for the sources and causes of human errors as they affect the total aeronautical transportation system structure. Based on such improved understanding, changes in the technological, procedural, ATC system, training, etc., aspects of the system structure can be evolved to remedy or improve weak points.

At present there is no national capability to support the flight simulation studies which are necessary for identifying and correcting the sources of human error associated with current and future air carrier operations. As one means to this end the National Aeronautics and Space Administration is planning a new Man Vehicle Systems Research Facility for Ames Research Center. The Man Vehicle Systems Research Facility is intended to address at least three issues requiring high operational fidelity in aviation safety research:

1) Full mission/full crew/multiaircraft/air traffic control (ATC) interactions in general,

2) Crew/avionics, crew/crew, and crew/ATC interactions which are design specific, and

3) Advanced technology cockpits and man-machine relationships therein.

Major investigations of these issues will have as basic purposes the enhancement of flight safety and improved performance — in essence the reduction of human error.

Human errors in aviation tend to be treated in terms of clinical and anecdotal descriptions. For a more concrete identification of the sources of human error, one must strive to separate original underlying and contributing causes from the circumstantial causes cited in official investigative reports. Furthermore, if one is to attempt correction of the sources of human error, their cause-effect relationships must be better quantified and categorized in concise statistical summaries. In short, a more specific quantitative classification of the sources of human error is needed, and that is precisely the subject of this report.

Meaningful quantification requires a sound underlying and unifying foundation in terms of mathematical models which subsume existing evidence, permit the planning of experimental measurements, guide the interpretation of results, and serve as the basis for extrapolation (e.g., by analysis and estimation) of results to other circumstances. Specifically needed in this connection are validated models of human behavior which permit the analyst to focus on the abnormalities which lead to human error. It is the purpose of this report to fulfill this need.

B. ORGANIZATION OF THE REPORT

The presentation begins with models of rational human behavior which represent specific and particular time sequences of operations. Section II provides a catalog and models of human perceptual and control behavior encompassing the entire range of man-machine system applications. The result views the human operator as having a triad of functional pathways, each one describing fundamentally different patterns of behavior and response performance.

Section III generalizes the foregoing presentation for other circumstances of particular importance to crew members and ground controllers in air carrier operations, viz., inputs other than visual, interactions among several presumed cooperators, and outputs other than manipulations. The most common example of these other circumstances in aircraft and the air traffic control system is, of course, voice communication.

Section III continues with a brief summary of the Successive Organization of Perception (SOP) theory for skill development. The SOP theory leads to an understanding of both progressive and regressive control, communication, supervisory, and monitoring behavior during training, transfer, rehearsal, and stressful operations. It is fundamental to an understanding of human error sources, and it can also be associated with at least one concept of perceptual motor loading.

Section III concludes with a practical example showing how to construct a temporal sequence of mission phase behavioral patterns from a knowledge of the normal constituent task behavior required of crew members during approach and landing operations. Of particular significance in this example is the fact that, depending on the nature of the man-machine interface, open-loop behavior in performing many so-called supervisory and discrete tasks is normally of limited duration and is properly interspersed or concluded with closed-loop behavior characterized in terms of an off-line supervisory monitor in the SOP theory. Omission of this closed-loop monitoring behavior may, in fact, lead to human error.

Section IV progresses from a description of the normal to the abnormal, i.e., from satisfactory to unsatisfactory error performance. This exposition begins with overall definitions and classifications of human error and system error. It then proceeds to consider a more detailed partition of circumstantial causes of human behavioral errors within the framework of the perceptually-centered input-output pathways embedded within the SOP paradigm. This section concludes with a breakdown of original underlying and contributing causes of human behavioral errors arranged to lead readily to categorical recommendations for correction of the causes of error.

Section V progresses from a description of the single specific task behavior to a description of ensembles of behavior, i.e., from models of specific instances to probabilistic generalizations. This exposition proceeds with the aid of monitoring and decision-making paradigms as devices for examining assembled data encompassing system performance and effectiveness as well as human error performance and behavior. Section V concludes again with practical examples applied to the approach and landing problem.

Section VI provides a concluding summary of the key points made about the several natures of human behavior and error offered in this report. The descriptions and characterizations presented here provide a number of bases for full mission simulation planning. These include the development of mission phase/task/human behavior breakdowns and task event and outcome descriptions. Also to be considered are the selection of appropriate state and control variables needed for the definition of system outcome probabilities and for the behavioral and error assessments for the human elements. The actual types of measurement procedures suitable for treating full mission simulations using the perspectives presented here are the subject of a forthcoming companion report.

SECTION II

A CATALOG AND MODELS OF HUMAN CONTROL BEHAVIOR

A. A PERCEPTUALLY CENTERED MODEL OF CONTROL BEHAVIOR

Because of enormous versatility as an information processing device the human controller is complicated to describe quantitatively. Three features are dominant in this versatility. First, the constituent sensing, data processing, computing, and actuating elements are connected as internal signal processing pathways which can be reconfigured as the situation changes. Second, functional operations on the internal signals within a given pathway may also be modified. Third, the output mechanism is selected to suit the circumstances. Thus, in general, we have selection of the pathways to be involved and of the output mode, and adaptation of the functions performed within the selected pathways. Although these features are common to most rational overt human behavior, their quantitative description and associations with the external environment have been studied primarily in a manual control context. Therefore, we shall approach a general model by first presenting one for manual outputs. This focuses on the pathways and adaptation within them. The resulting restricted model can then be modified as needed to fit other output modes. This procedure permits concepts to be concretely presented while remaining closely tied to an extensive empirical base.

Figure 1* shows the general pathways needed to describe human behavior in an interactive man/machine system wherein the human operates

---

*The description of human control operations given here has an extended history, and constitutes a synthesis of a vast experimental literature and the work of many people. It was started with Ref. 1 and has been elaborated and extended at intervals since, e.g., with Refs. 2 and 3. These references include a comprehensive coverage of sources.

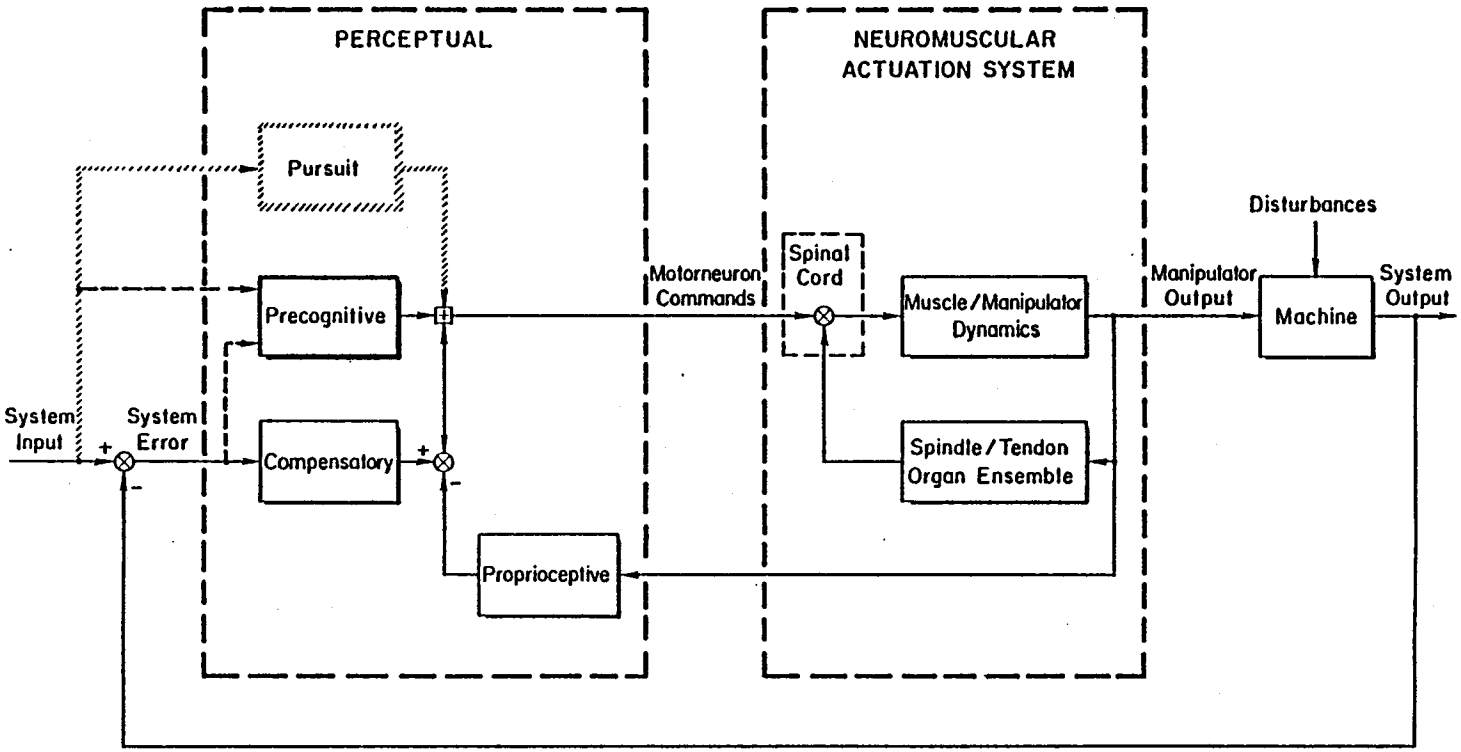


Figure 1. Major Human Controller Pathways in a Man-Machine System

on visually sensed inputs and communicates with the machine via a manipulative output. Each block represents a transfer of signals from its input to its output. The complete block diagram shows the minimum number of the major internal functional signal pathways required to characterize the different varieties of human controller behavior. That the specific internal signal organizational possibilities shown are actually present was originally demonstrated by manipulating experimental situations (e.g., by changing system inputs and machine dynamics). By this means one can isolate different combinations of the specific blocks shown in this diagram.

To describe the components of the figure start at the far right with the controlled element; this is the machine being controlled by the human. To its left is the actual interface between the human and the machine — the neuromuscular actuation system, which is the human's output mechanism considered here. This in itself is a complicated feedback control system capable of operating as an open-loop or combined open-loop/closed-loop system (although these levels of complication are not explicit in the simple feedback control actuation system block diagram shown here). The neuromuscular system comprises limb, muscle, and manipulator dynamics in the forward loop and muscle spindle and tendon organ ensembles as feedback elements. All these elements operate within the human at the level from the spinal cord to the periphery.

There are other sensory sources, such as joint receptors and peripheral vision, which indicate limb output position. These operate through higher centers and are subsumed in the proprioceptive feedback loop incorporating a block at the perceptual level further to the left in the diagram. If motion inputs are present, these too can be associated in a proprioceptive-like block.

The three other pathways shown within the perceptual level are responsible for major differences in purposeful behavior. Each pathway accounts for a different level of excellence in skilled performance and, accordingly, will also account for undesirable human errors which may appear. Stated another way, the three pathways correspond to three different types of control operations on the visually presented system

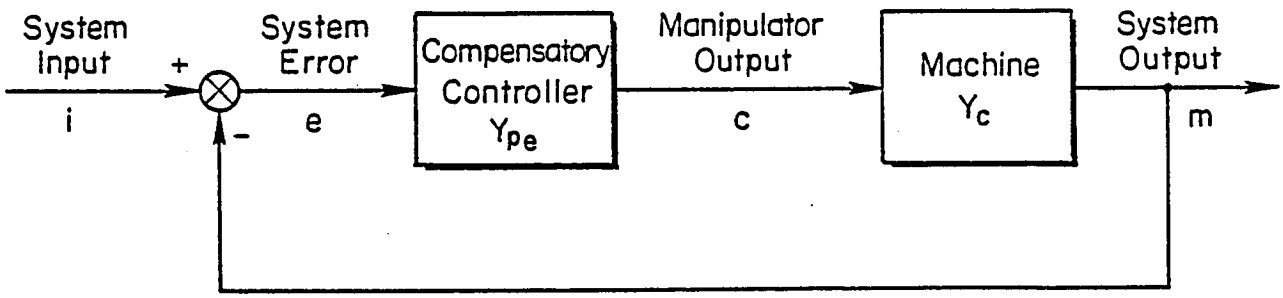
inputs. Depending on which pathway is effectively present, the control structure of the man/machine system can appear to be open-loop (precognitive), or combination open-loop/closed-loop (pursuit), or totally closed-loop (compensatory) with respect to visual stimuli.

B. COMPENSATORY OPERATIONS

The compensatory block is appropriate at the perceptual level when the human controller acts in response to system errors or controlled element output quantities. When only this pathway is operating the human exerts closed-loop control on the machine so as to minimize system errors in the presence of command and disturbance inputs. Compensatory behavior will be present when the commands and disturbances are random-appearing and when the only information displayed to the human controller consists of system errors or machine outputs.

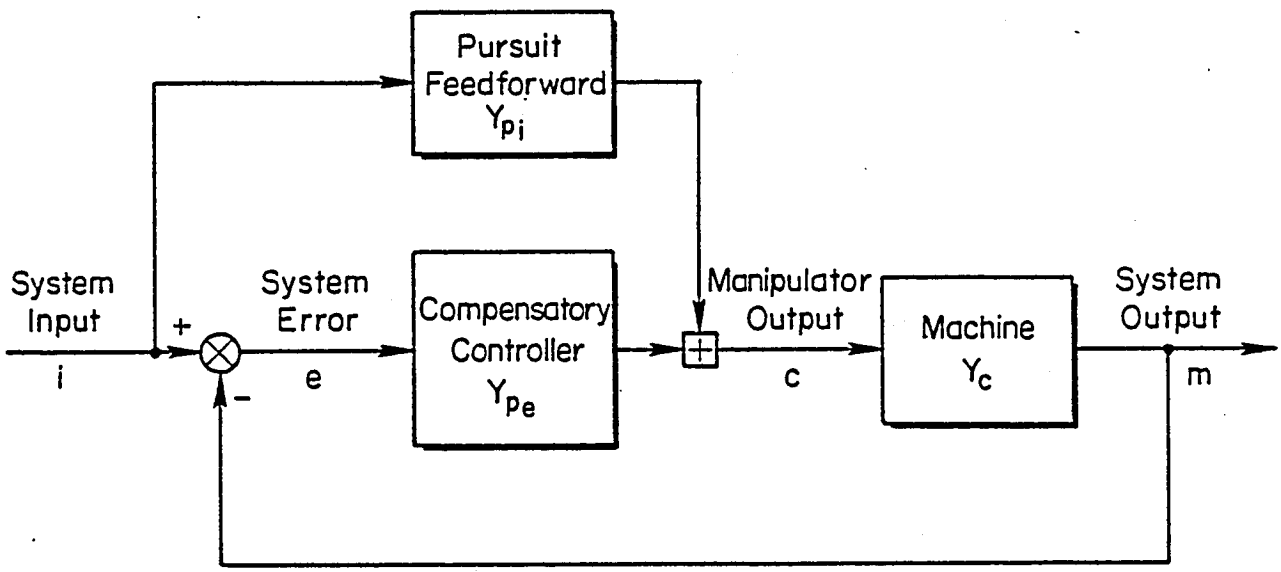
The term "system errors," as used here, refers to mismatches between system inputs and outputs. These "errors" are the essential stimuli to the human controller for closed-loop operation. Because they are the sine qua non of feedback control, they are not intrinsically undesirable. In fact, when a compensatory system is operating properly the human controller is effective in system error reduction or correction by dint of good use of error as a stimulus. On the other hand, we shall later see that compensatory system operations can give rise to errors which, while just as human-based as those described here, are undesirable because of their size or character.

The compensatory pathway is shown in isolation in Fig. 2a. Because the human can operate only on the error, the system output, m, can be made to follow the system input, i, over the control bandwidth only to the extent that $|Y_{p_e} Y_c|$ is made much greater than 1 by the controller (Y_{p_e}), i.e.,



$$\frac{M}{I} = \frac{Y_{pe}Y_c}{1+Y_{pe}Y_c} \quad , \quad \frac{E}{I} = \frac{1}{1+Y_{pe}Y_c}$$

a) Compensatory System



$$\frac{M}{I} = \frac{Y_c(Y_{pi}+Y_{pe})}{1+Y_{pe}Y_c} \quad , \quad \frac{E}{I} = \frac{1-Y_cY_{pi}}{1+Y_{pe}Y_c}$$

b) Pursuit System

Figure 2. Functional Block Diagrams of Compensatory and Pursuit Man-Machine Systems

$$\frac{M}{I} = \frac{Y_{p_e} Y_c}{1 + Y_{p_e} Y_c}$$

$$\doteq 1 \qquad \text{for } \omega \text{ such that } |Y_{p_e} Y_c(j\omega)| > 1 \qquad (1)$$

Similarly, the error, e, is reduced only in the frequency regime where $|Y_{p_e} Y_c|$ is large when compared with unity.

The details of what the human controller does in adjusting his Y_{p_e} to achieve error reduction have been the subject of thousands of experiments. Consequently, most of the adaptive features (i.e., adaptive within the compensatory pathway) associated with these kinds of operations are well understood (Ref. 3).

If a large variety of controlled element forms are used in an experimental series, the measured human transfer characteristics will be different for each controlled element. But, for a very wide range of controlled element dynamics it turns out that the form of the total open-loop transfer characteristic about the crossover frequency will remain substantially invariant. This form is

$$Y_{p_e} Y_c \doteq \frac{\omega_c e^{-j\omega\tau_e}}{j\omega} \quad , \qquad \omega \sim \omega_c \qquad (2)$$

The effective system latency or time delay, τ_e, which is only a low-frequency approximation to all manner of high-frequency leads and lags deriving from both the man and the machine, is not a constant. The operator-based portion, τ_o, of τ_e depends primarily on the amount of lead equalization required of the operator, as shown in Fig. 3 (Ref. 3). This indicates that the human controller's equalization adopted to offset controlled element dynamic deficiencies has an associated computational time penalty. With this proviso on τ, the Eq. 2 relationship

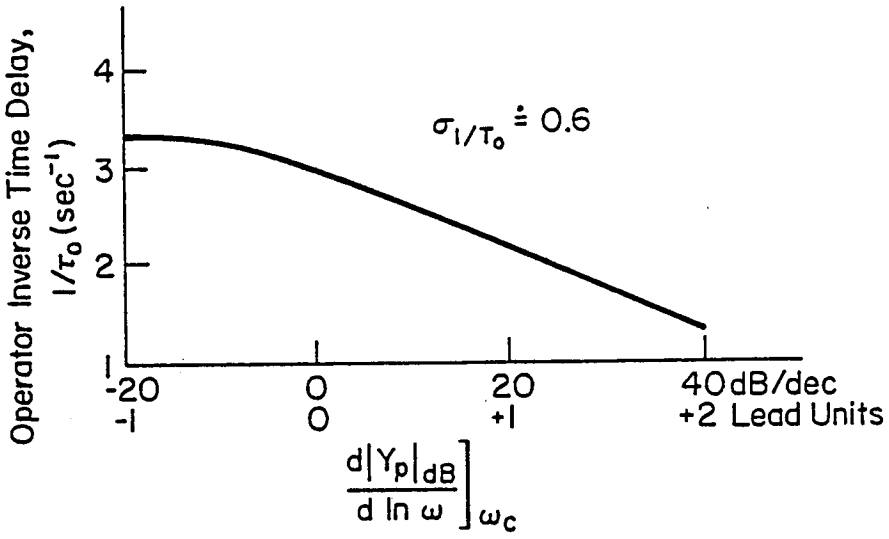


Figure 3. Crossover Model Dynamic-Stimulus-Response Latency as a Function of Operator Lead Equalization

becomes the well-known simplified crossover model of compensatory manual control theory.*

The human operator's adaptation to controlled element dynamics is implicit in the Eq. 2 relationship, i.e., for a particular set of controlled element dynamics defined by Y_c the human will adopt a crossover region transfer characteristic $|Y_{p_e}| \doteq |\omega_c/sY_c|$. The general form of the human's response would thus be determined by the specifics of Y_c, and changes in this task variable evoke changes in Y_{p_e} such that the crossover model open-loop transfer characteristic form is preserved.

Because we shall ultimately be interested primarily in error it is pertinent to recognize that the crossover frequency, ω_c, which corresponds to the frequency where $|Y_{p_e} Y_c| = 1$, divides the frequency domain into two fundamental regions. For inputs which have a frequency content much less than ω_c, $|Y_{p_e} Y_c|$ will be much greater than 1, so the output

* A simplified derivation of the crossover model from empirical data for several different controlled elements, together with its many useful mathematical properties, is given in Chapter II of Ref. 3.

m(t) will follow the input i(t) almost exactly and error, e(t), will be reduced relative to i(t). That is,

$$\left|\frac{E}{I}\right| = \left|\frac{1}{1 + Y_{p_e} Y_e}\right|$$

$$\doteq \frac{\omega}{\omega_c} \quad , \qquad \text{when } |Y_{p_e} Y_c| > 1 \tag{3}$$

On the other hand, for input frequencies greater than ω_c the error will not be reduced and, instead, will be approximately equal to the input.

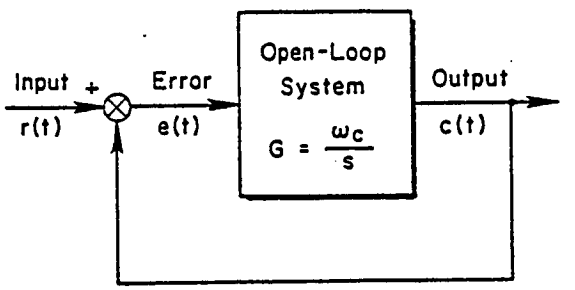
The crossover frequency is a close approximation to the ystem bandwidth, which for low pass systems is the frequency where $|M(j\omega)/I(j\omega)| = -3$ dB. Bandwidth is the usual metric used to describe the frequency regions over which the output is a good duplicate of the input. Bandwidth is also connected with the response time of a system, large bandwidth implying rapid response. These connections are illustrated for the special case of the crossover model with $\tau = 0$ in Fig. 4. In these circumstances the bandwidth of the closed-loop system and the crossover frequency, ω_c, of the open loop are identical, while the time constant of the closed-loop system is simply $1/\omega_c$. For more complex systems (e.g., $\tau \neq 0$ for the crossover model of Eq. 2), there is a difference between the bandwidth, ω_b, and the crossover frequency, ω_c, yet they are ordinarily relatively close to each other. In any event, they are parameters which co-vary as system properties are changed.

Because bandwidth, or crossover frequency, is the primary measure of error reduction in compensatory systems, the dependence of ω_c on the controlled element characteristics is of major importance. The general nature of the variation can be appreciated using Fig. 3. To use this figure we first recall that the phase margin of a closed-loop system is defined as the difference between 180 deg and the phase angle of the open-loop characteristic at the crossover frequency. For the crossover model,

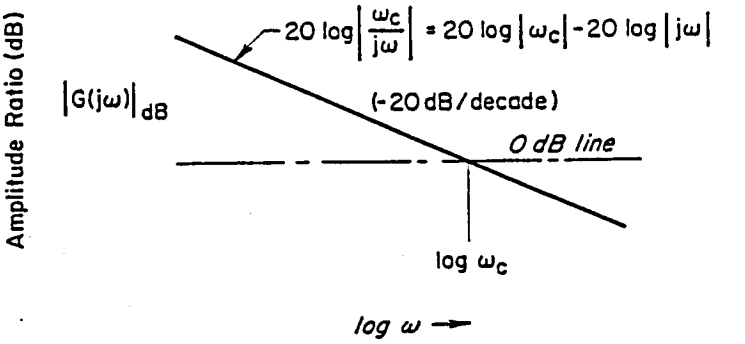
$$\phi_M = \pi - (\pi/2 + \omega_c \tau_e)$$

$$= \pi/2 - \omega_c \tau_e \tag{4}$$

CLOSED-LOOP SYSTEM

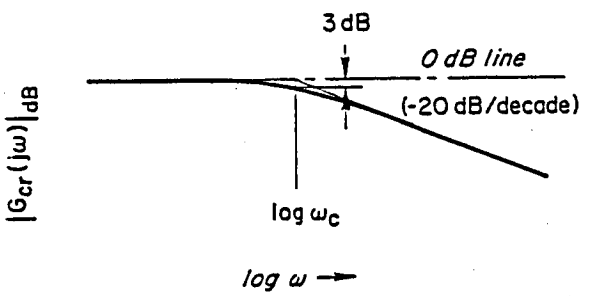


OPEN-LOOP CHARACTERISTICS



CLOSED-LOOP INPUT-OUTPUT CHARACTERISTICS

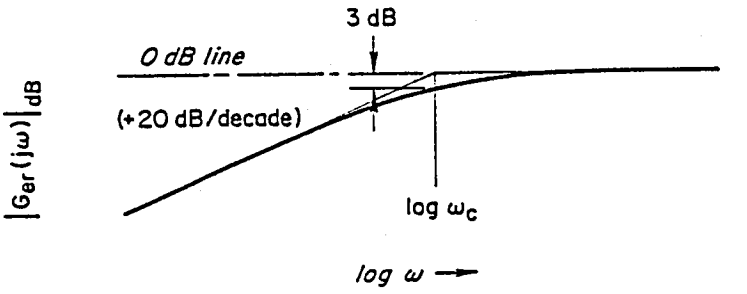
$$G_{cr} = \frac{G}{1+G} = \frac{1}{(s/\omega_c)+1}$$



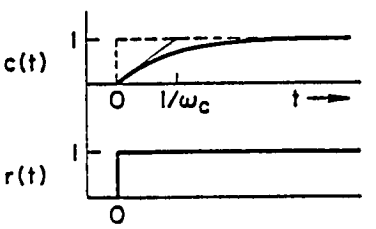
jω - Bode Diagram

CLOSED-LOOP INPUT-ERROR CHARACTERISTICS

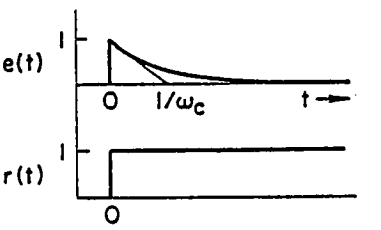
$$G_{er} = \frac{1}{1+G} = \frac{(s/\omega_c)}{(s/\omega_c)+1}$$



jω - Bode Diagram



Indicial Response



Indicial Response

Figure 4. Crossover Frequency, Bandwidth and Time Responses for an Elementary Closed-Loop System

Then for simplicity, and to connect with Fig. 3, assume that the operator adopts a common phase margin of $\pi/2 - 1$ radians for all controlled elements to be considered. For this condition the crossover frequency will be $1/\tau_e$ rad/sec, which is shown as the ordinate on Fig. 3 (assuming ($\tau_e \doteq \tau_o$). Using the crossover model, Eq. 2, the leads generated by the operator, given by the abscissa in Fig. 3, at the 0, 20, and 40 dB/dec points are seen to correspond to machine dynamics of $Y_c = K/s$, K/s^2, and K/s^3, respectively. Then, reading from the figure, the ω_c's (or approximate bandwidths) for the closed-loop systems involving these plants (when $\phi_M = \pi/2 - 1$ rad) will be about 3, 2.15, and 0.35 rad/sec, respectively. For a pure gain controlled element an ω_c of 3-5 rad/sec is readily achieved.

The crossover model also applies when the machine dynamics are smoothly time varying. The crossover frequency itself tends to be constant for a given set of task variables whenever the large amplitude high-frequency components in the system input are much less than ω_c. It increases slightly as forcing function bandwidth is increased and is reduced for very small input amplitudes. This is a consequence of the operator's indifference threshold, which is the most important nonlinearity to be considered in connection with crossover model transfer characteristics. It is used to account for inattention, among other things. We shall return later to some of these properties of compensatory systems when considering sources of human errors in Section IV.

C. PURSUIT OPERATIONS

When the command inputs can be distinguished from the system outputs by virtue of the "display" (e.g., i and m are shown or detectable as separate entities relative to a reference) or preview (e.g., as in following a curved pathway), the pursuit pathway joins the compensatory. This new pathway, Y_{p_i} in Figs. 1 and 2, provides an open-loop control in conjunction with the compensatory closed-loop error correcting action.

Perhaps the most mundane example is driving a car (see, e.g., Ref. 4). When there is sufficient roadway preview and contrast and texture in the surround to permit perception of the roadway and the vehicle output motions as independent entities, the practiced driver can take advantage of this preview to structure the control feedforward, Y_{p_i}. This open-loop feedforward element permits the driver to anticipate the desired path. After the driver has also learned to compensate for the vehicle dynamics, the driver feedforward portion can cause the vehicle to very nearly duplicate the desired path input. This kind of system is sometimes called open cycle, closed cycle, in which the major commands come from the feedforward (open-loop) element, while the closed-loop portion of the system acts as a vernier control to reduce any residual errors.

As shown by comparison with compensatory operation in Fig. 2b, there are substantial advantages intrinsic to pursuit control. The same source of error reduction available in compensatory operations, Y_{p_e}, is still present, with similar effects to those described above. But the feedforward Y_{p_i} offers an additional pathway for error reduction. In fact, if $Y_{p_i}Y_c \doteq 1$ over the system bandwidth, the error will be approximately zero regardless of the value of $Y_{p_e}Y_c$. When this latter quantity is also large (as in the compensatory case), the quality of closed-loop control can be very good indeed.

We can again use closed-loop system bandwidth as a convenient metric of system response and error-reduction quality. A surrogate bandwidth measure which is compatible with the compensatory system's crossover frequency is desirable. This can be done by using the crossover frequency found from an equivalent open-loop transfer characteristic, M/E. Using the relationships in Fig. 2b this is seen to be

$$\frac{M}{E} = \frac{Y_c(Y_{p_i} + Y_{p_e})}{1 - Y_cY_{p_i}} \tag{5}$$

Systen bandwidths as high as 1 Hz or so are possible for pure gain ($Y_c = K_c$) or rate control ($Y_c = K_c/s$) controlled elements.

D. PRECOGNITIVE OPERATIONS

An even higher level of control is possible. When complete familiarity with the controlled element dynamics and the entire perceptual field is achieved, the operator can generate neuromuscular commands which are deft, discrete, properly timed, scaled, and sequenced so as to result in machine outputs which are exactly as desired. These neuromuscular commands are selected from a repertoire of previously learned control movements. They are conditioned responses which may be triggered by the situation and the command and control quantities, but they are not continuously dependent on these quantities. This pure open-loop programmed-control-like behavior is called precognitive. Like the pursuit pathway, it often appears in company with the compensatory operations as a dual-mode control — a form where the control exerted is initiated and largely accomplished by the precognitive action and then may be completed with compensatory error-reduction operations.

An example of precognitive behavior is provided by experiments with step-like system inputs into a man/machine system with no disturbances. Even with a compensatory display which shows only the system error the operator's inaction during his initial reaction time interval permits the step input to be completely perceived once it is applied. Thus, the input is completely known. Similarly, by dint of extensive practice, the dynamics of the machine can also be thoroughly imprinted, and an appropriate control repertoire established. Responses for such systems, with controlled element dynamics of $Y_c = K_c/s^2$ and K_c/s^3, are shown in Fig. 5 (taken from Ref. 5). The operator's output control movements are somewhat rounded off, but nevertheless have the essential bang-bang character of time-optimal control. After the operator's initial dead time the control movements are quite similar to the responses of an ideal limited-output programmed controller operating to obey a minimum time criterion. The limited control deflection is an internal constraint imposed by the operator for the given situation and is not necessarily a physical limit. Feedback is present only to the extent required for the human to estimate the appropriate switching points when

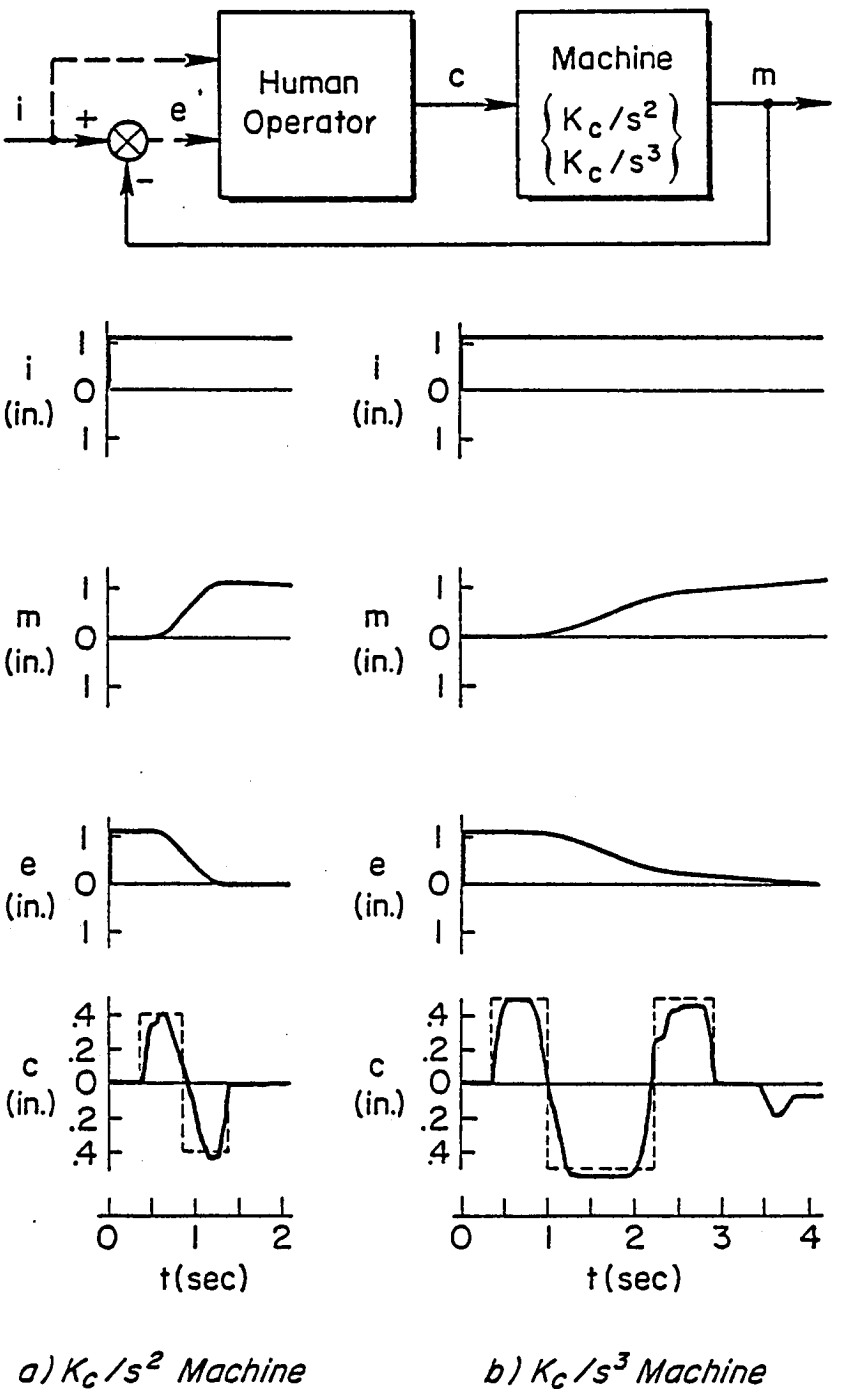


Figure 5. Step-Input Responses Exhibiting Precognitive Control

the phase trajectory intersects the time-optimal switching surfaces. Because the task is thoroughly learned and practiced, the delays internal to the operator (after the initial reaction time to the randomly applied step) are internally accounted for and a time-optimal control paradigm is suitable for the main transient control action. After the error is reduced to very small values, the feedback afforded by the compensatory pathways is utilized to maintain the error within reasonable bounds. (This dual-mode action of the human is entirely consonant with the dual-mode programmed controllers normally required to achieve practical time-optimal control).

For modeling purposes, precognitive operation can be conceived as a series of decision algorithms and stored programs. An elaboration of the Fig. 1 precognitive channel is shown in Fig. 6. The components are a stored repertoire of learned responses and a decision rule which examines the perceptual patterns of system input cues to determine which item in the repertoire to release and when to trigger it. Possibilities shown include synchronous operation, refinement of the pursuit feedforward, and various "programmed" responses. The precognitive block can also be thought of as a special feedforward in which the input serves only to provide a cue for the activation of a programmed controller.

Finally, when "error" reduction is considered, the very existence of precognitive control is highly input-sensitive. In most cases the input is discrete and step-like — a classical discrete stimulus to action. However, the tracking of periodic functions can also progress to a precognitive phase where the internal "synchronous generator" of Fig. 6 is the actual source of the human's output response. Using data from experiments with these kinds of system inputs indicates a "bandwidth" of 2-3 Hz for precognitive operations with a pure gain controlled element.

The approximate numerical values for "bandwidth" cited above for pure gain controlled elements are summarized in Table 1.

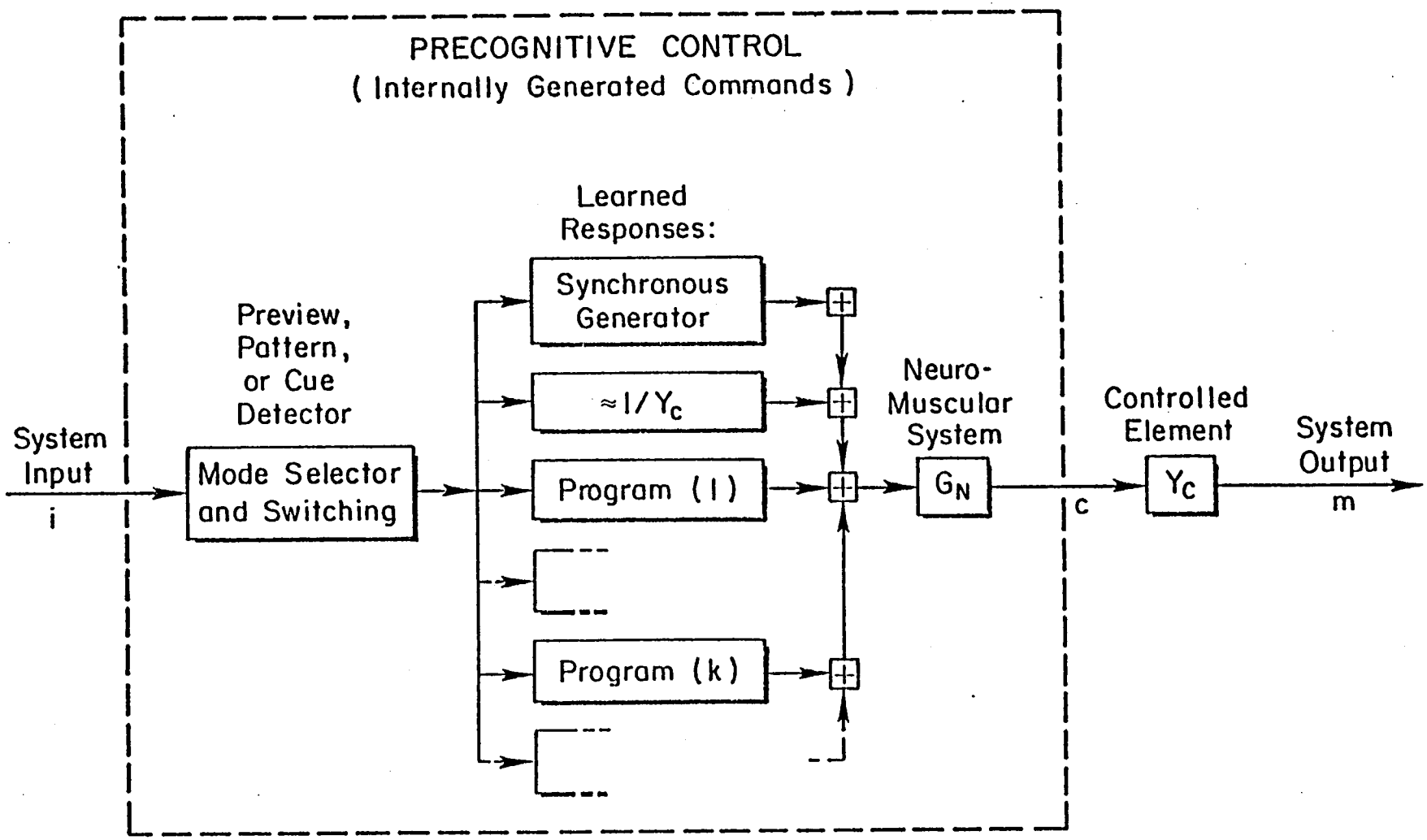


Figure 6. Elaboration of Precognitive Control Pathway

TABLE 1

APPROXIMATE SYSTEM "BANDWIDTH" FOR $Y_c = K_c$

Compensatory	4 rad/sec
Pursuit	6 rad/sec
Precognitive	12 rad/sec

E. ATTENTION AND ASSOCIATION

In general, measurements of human behavior in man/machine systems can be affected by a very large number of variables. Some of these are depicted in Fig. 7, categorized under the headings of Task, Environmental, Procedural, and Operator-Centered Variables. The human's outputs are also expanded in this diagram to include physiological and psychophysiological aspects as well as control actions. In limiting circumstances all of the variables can exert important effects on human operations, but most simply define an insensitive, uniform background insofar as control operations conducted in a relatively benign environment are concerned.

Two Operator-Centered Variables are, however, of key importance to the three limiting forms of manual control behavior described above. These are attention and association plus response set.

Attention implies the ability to sense and perceive stimuli as well as readiness to respond to selected stimuli. By analogy with visual perception studies we can conceive of an attentional field, with a principal focus and bordering margins. The attentional field has both spatial geometric and intensity aspects. Thus, inattention or impaired attention can result in a narrowing of the margins, an increase in the minimum stimulus needed to cause an operator output, or both. The intensity aspect of attention is treated in manual control theory by an indifference threshold. A reduction in attentional field intensity then results primarily in a change in operator gain and need not cause any increased latencies.

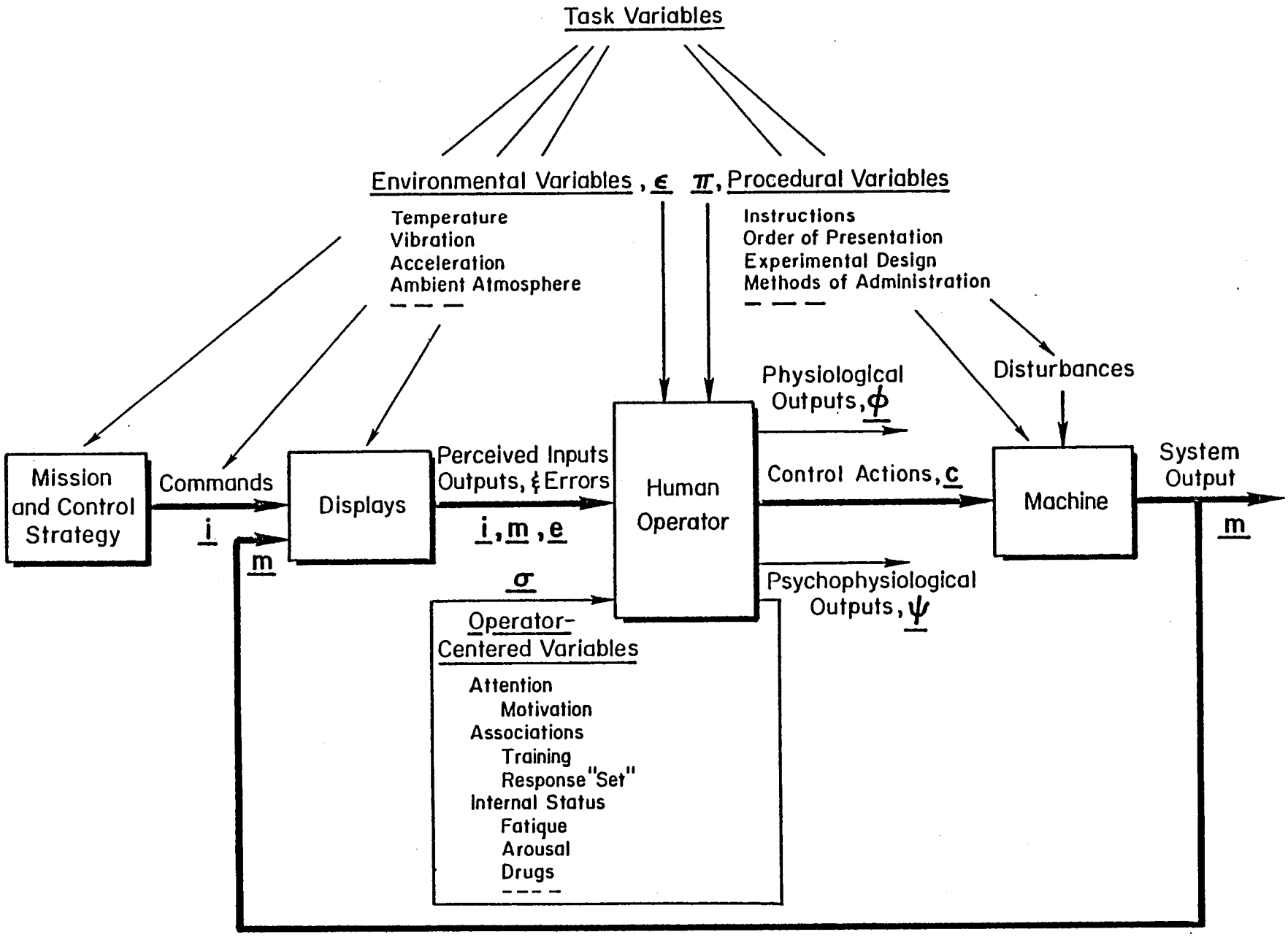


Figure 7. Variables Which Affect the Man-Machine System

Clearly, the breadth and scope of attention must be more expansive for pursuit than for compensatory pathways, if for no other reason than that more inputs are being taken into account. A reduction in attentional margins on a pursuit display, which provides input, i, and output, m, as well as the error e, can narrow to observation of e alone. The reponse would become compensatory, since Y_{p_i} cannot then be generated.

By association we mean generally the connection of sensations and perceptions with characterizing and stable features of previously observed stimuli so that the previously learned repertory involved in precognitive control can be released. Response set, itself, is that set established by particular past experimental experience. Both association and connected response sets are essential for the development and continued existence of precognitive behavioral patterns.

F. OPERATOR-INDUCED NOISE

The human controller is not noise-free. In addition to those output components which are causally related to the system inputs and disturbances there is another component in the operator's response which is operator-induced noise, often referred to as "remnant." In systems with linear manipulators the remnant is a continuous, relatively broadband, power spectral density which scales approximately with the mean-squared error. This kind of noise can, in principle, result from several sources, but in single-loop systems with linear manipulators the basic cause appears to be random time-varying behavior within the operator primarily associated with fluctuations in the effective time delay. This can be interpreted as a random change in phase, akin to a random frequency modulation, or to variations of internal sampling rate in a sampled data interpretation of the operator (Refs. 1-3, 6-10). Additional noise sources are present in systems which are multiloop in that their control requires the use of information gained from several "display" sources. Because both parafoveal and foveal visual pathways can operate in parallel, essentially continuous signals from a particular display element can be available to the operator even when the eye

is scanning. The essence of past work in man/machine systems involving many displays (Refs. 3, 11-15) shows that:

1. A fairly stationary scanning strategy evolves for a given task and display array.

2. The operator's output control motions are essentially continuous even though the foveal eye fixations are discrete.

3. The first-order effects of scanning are to reduce controller gains and increase remnant in the scanned channels.

The effects listed third are of most interest here, as they lead to both decreased system bandwidth and increased controller-induced noise. The degree of gain reduction depends on parafoveal viewing angle and relative parafoveal to foveal dwell times.

C. SOME EXEMPLARY DATA FOR COMPLEX SYSTEMS

The three-phase perceptually centered model of control behavior described above has been developed to account for an enormous variety of empirical results. The theory permits, even invites, the detailed quantitative measurement of human input/output characteristics and operator-induced noise properties as fundamental measures of human dynamic behavior. Thus, complete descriptions of man/machine systems would incorporate describing functions and remnant power spectral densities. From these fundamental measures all of the more conventional measures of system performance, such as mean-squared errors, mean-squared controller outputs, mean-squared system outputs, power spectral density, and average axis crossings, etc., of various system signals, can be computed. When our focus is on nominal error and its occasional escalation to intolerable values, some far simpler metrics can be used. For example, in scenarios which can be considered stationary in some sense, the effective system bandwidth is a suitable descriptor for the dynamics of information transfer between input and output and the frequency range over which system error is reduced relative to the system input. Similarly, the gross effects of remnant, for a given system bandwidth, can be assessed by mean-squared values of system outputs or errors. (Bandwidth must be

fixed for mean-squared outputs or errors to be unequivocal indicators of remnant changes since mean-squared values are integrals of system transfer properties operating on remnant power spectral densities.) To gain some appreciation for typical numbers we shall cite here some results from several experimental scenarios for complex man/machine systems.

1. Compensatory and Pursuit Bandwidth Differences in a Complex System

The first set of data (Ref. 4) considers comparisons between pursuit and compensatory operations in automobile driving. (There are, unfortunately, no extensive data for this type of comparison for flight path control tasks. Nonetheless, the vehicle dynamics are similar enough to aircraft for the bandwidth differences to be considered indicative of what would happen in flight.) The experiment was conducted in a fixed-base simulator which had a line-drawn roadway display and two-degree-of-freedom steering dynamics for the car. Both wind disturbances and road curvature commands were injected into the system in order to measure the driver's behavior and response. The wind disturbance was used with the straight road to identify the driver's compensatory dynamics. With this disturbance the driver is not aware of the input until the car responds. In the winding road case the road curvature and other features are of course directly perceivable by the driver through preview of the road. The data for six subjects, when converted to effective system crossover frequency, appear as Table 2.

TABLE 2

SYSTEM BANDWIDTH COMPARISONS FOR PATH CONTROL

System Organization	Controller Pathways Involved	Bandwidth [Effective Crossover Frequency] (rad/sec)
Compensatory	Y_{p_e}	1.3
Pursuit	Y_{p_e}, Y_{p_i}	2.2

These fixed-base data do not include the effects of the human's motion sensing apparatus, so all of the lead required to offset the automobile's lags must be accomplished using the visual channels. When motion compatible with visual cues is present, as in the real automobile, direct experimental measurements demonstrate that the necessity for visually generated lead is reduced. The primary effect of the compatible motion feedbacks can be converted into a visual-only equivalent by reducing the effective time delay in the crossover model. This permits the system bandwidth to be greatly increased. For example, in an extensive full-scale experimental series (Ref. 17), crossover frequencies near 4 rad/sec were achieved for compensatory driving.

Precognitive control can also be demonstrated in many driver/automobile maneuvers, such as single and double lane changes, obstacle avoidance, slaloms, etc. All of these involve highly practiced, learned maneuver response patterns. Several of these are illustrated in Ref. 4, including some slalom runs wherein the driver/vehicle system exhibits a 2.5 rad/sec periodic maneuver through a series of cones with no phase lag relative to the cones.

2. Attentional Focus Shifts (Scanning Effects)

The effects of scanning of the attentional focus can be illustrated with results from an experimental series where pilots flew Category II ILS approaches in a fixed-base DC-8 simulator (Ref. 18). A conventional instrument panel and controls were used with simulated vertical gust and glide slope beam bend forcing functions. A number of conditions were investigated, but the two most appropriate for our present interest compared approaches using a flight director with approaches using the full instrument panel. The pilot had to control both the lateral and longitudinal motions of the aircraft, and the situation with both display treatments was compensatory. The data shown in Table 3 are for only one pilot and are averaged for the available runs. In the flight director situation the attentional focus was on the flight director for about 75 percent of the time with 10 percent on the HSI/GSD and the remaining time spent monitoring altitude and airspeed. For the full panel display

TABLE 3

EFFECTS OF ATTENTIONAL FOCUS SHIFTS ON ALL-AXIS INSTRUMENT APPROACH TASK

Display	Bandwidth [Effective Attitude Control Crossover Frequency, ω_{θ_c}] (rad/sec)	System Performance [RMS Beam Deviation] (ft)
Flight Director	1.2	24
Full Panel	1.14	37

the HSI/GSD was the focus of attention 55 percent of the time, with attitude requiring 35 percent. The rest of the available time was again spent monitoring the indicated airspeed and altitude. It is interesting to note that the major instruments surveyed in both cases were close enough together to permit excellent parafoveal viewing while the pilot fixated foveally on the other primary instruments. This accounts for the essentially equal bandwidths achieved with each display arrangement. On the other hand, there was substantially more scanning required for the full panel version of the task than for the flight director, and this additional scanning gave rise to larger pilot remnants. The differences in system performance, measured here by rms beam deviation, stem primarily from this characteristic. With beam bends and turbulence, the pilot was fully occupied with both display configurations.

3. Reduction of the Attentional Field Boundaries

Another facet of attentional field effects can be illustrated with data from studies relating driver/vehicle system dynamics with field of view and roadway delineation. In the same simulator as that used for the data of Table 2 the spatial characteristics of the driver's visual field were modified by display adjustments. For the compensatory task (straight road with random wind disturbances) the extent of the visual segment was set to range from essentially unlimited visibility (300 ft)

to highly restricted visibility (50 ft). The key driver/vehicle characteristics were then measured in crossover model form. The results for ω_c and τ are given in Table 4. As an aside, it should be indicated that the vehicle dynamics and the driver's lead equalization were essentially invariant with changes in visibility. The results shown in Table 4 indicate that an external modification in the extent of the visual field results in both a reduction of the system bandwidth as measured by the crossover frequency and a concomitant reduction in the system stability as indicated by the increased latency. Driver workload and anxiety levels are high for the externally imposed reduced-attention field, as would be expected. This is exactly the opposite of the type of attention diminuation associated with an increased indifference threshold yet the result is the same when viewed as a system bandwidth.

TABLE 4

EFFECTS OF ATTENTIONAL FIELD COMPRESSION

Visibility (ft)	Bandwidth [Crossover Frequency] (rad/sec)	System Latency [Effective τ] (sec)
300	1.5	0.53
50	1.3	0.62

SECTION III

A PERCEPTUALLY CENTERED MODEL OF HUMAN BEHAVIOR

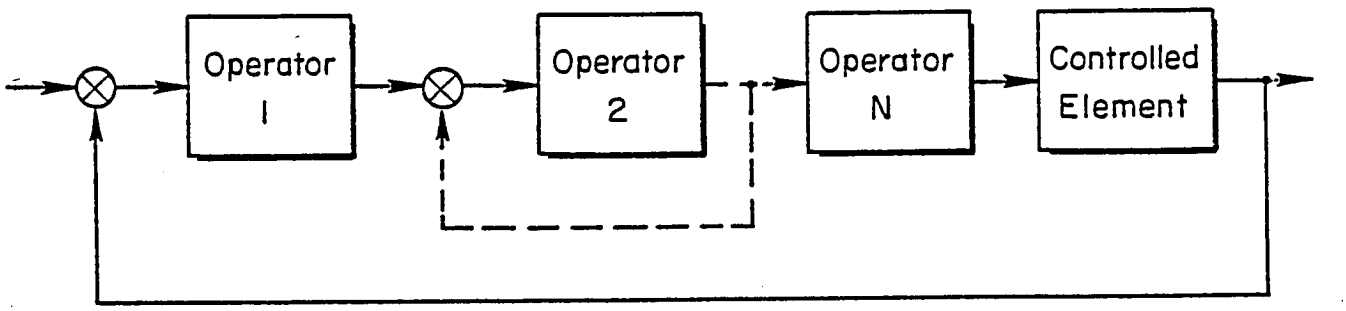
A. GENERALIZATION OF THE PERCEPTUALLY CENTERED MODEL OF CONTROL BEHAVIOR

The overall and subordinate (for each pathway) models described in the previous section have emphasized the visual modality as the input and manual manipulation as the human's output. The very extensive data base on which the model synthesis is founded involves single operators in close interaction with machines. In this section we shall propose a generalized view of this model in which the three phases — compensatory, pursuit, and precognitive — of operation on system inputs are retained, but wherein the inputs themselves are not restricted to the visual modality and the outputs are not restricted to manual manipulation. In other words, we will propose here a model of human behavior for general inputs and outputs which incorporates operational modes which are more or less continuously closed loop, partially closed loop and partially open loop, and primarily open loop in character. For tasks which fit these general paradigms the appropriate measures and understanding can be carried through more or less directly by analogy with the control model descriptions. Thus, for example, the bandwidth as a characterization of system dynamics and error reduction potential can be carried over into other systems involving men and machines.

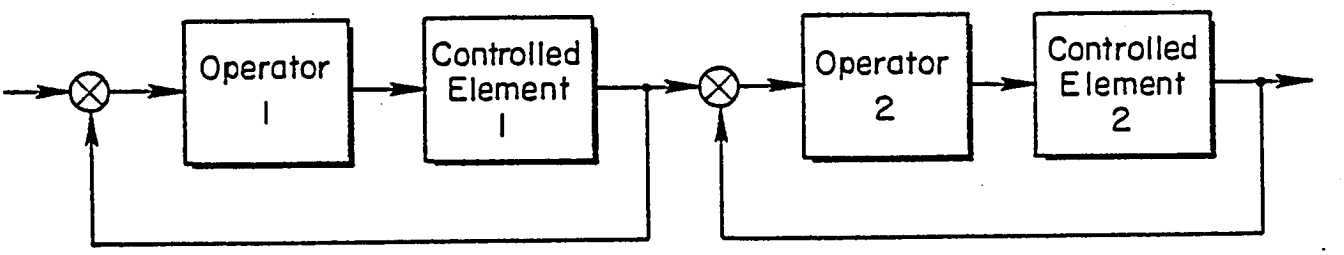
The first generalization needed is at the input end. The description of pathways available for human control activities described in Section II has emphasized the visual modality. Similar behavior patterns are present in the aural modality and at least to some extent with appropriate tactile stimulation. In fact, compensatory and precognitive control behavior has been demonstrated with aural, tactile, and motion inputs, and presumably some form of pursuit is also possible. In contrast to vision, the data bases are unfortunately rather limited for these sensory channels.

The second generalization is from man to men in the human control portions. The use of measurement techniques associated with manual control to such systems is a natural extension, and indeed was applied at an early date (Refs. 19-21). The simplest multi-operator systems are ganged in series, as shown in Fig. 8a. In systems where the operators are in sequence, i.e., the output of one operator is the input to the next, the overall system bandwidth deteriorates markedly as the number of operators increases. Because of the adaptive properties of the operators, each changes his own behavior so as to adapt it to the behaviors of the others and, as would be expected, this takes a far longer time than in a system with one operator. There also appears to be an upper limit, in that even with unity controlled element dynamics, stabilization of the system could not be attained with four operators in spite of many trials (Ref. 20). As one would expect, the mutual adaptation phenomenon can be eliminated by providing an inner-loop feedback around some of the intermediate operators, as shown by the dashed feedback loop in Fig. 8a. The operator with a minor loop is insensible of the main feedback path and adapts his behavior to the minor closed loop with which he is confronted. A limiting case of this type of control is shown by the closed-loop systems in series of Fig. 8b. Here one subsystem transmits its output directly as an input to the subsequent subsystem. For this kind of operation there is no inherent stability problem although the bandwidth of the overall system will decrease as the number of operator units increases. This can be appreciated from the data (Ref. 20) for one, two, and three operators in series shown in Fig. 8c.

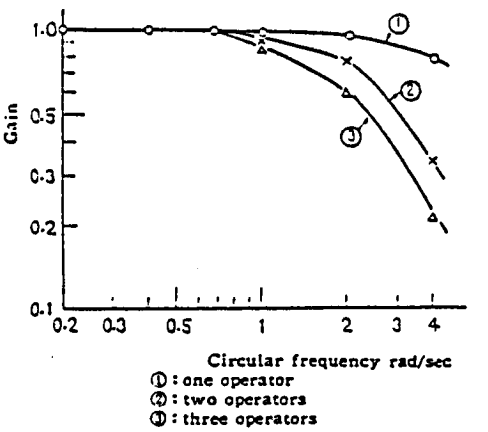
The third important generalization relates to the operators' output. This need not be a physical manipulation but can incorporate other means of transmitting signals. The most common in aircraft and the air traffic control system is voice communication. An example which is applicable to some ATC operations is given in Ref. 19. Here, one person observed an error from a display and communicated voice commands to a second operator. In the Ref. 19 experiments the director commanded the amount of correction by saying, for example, "left, ... left, ... right, right, right,...left, ...," etc., with the tracker moving his control handle a prescribed amount at each command. In this situation, the director was



a) Operators in Series



b) Closed-Loop System in Series



c) Total System Amplitude Ratios for Closed-Loop System in Series: (all controlled elements with unity dynamics, Ref. 21)

Figure 8. Multi-Operator Systems

making the intelligent decisions involved in correcting the error and translating these to discrete, quantized commands to be followed by the tracker. The system bandwidth for this kind of operation was roughly one-third that of a single operator system with the same controlled element.

These generalizations as to operator inputs and outputs, as well as extensions to multiple operator systems, permit us to generalize the human part of Fig. 1 as shown in Fig. 9. Here the system inputs and errors may appear in several sensory modalities, and the motor subsystem output may be manipulative or verbal. As we have already described for the manual control case, the pathway used in a particular circumstance is the result of the nature of the perceptual field and of training. Table 5 summarizes these and other facets of the perceptually centered model.

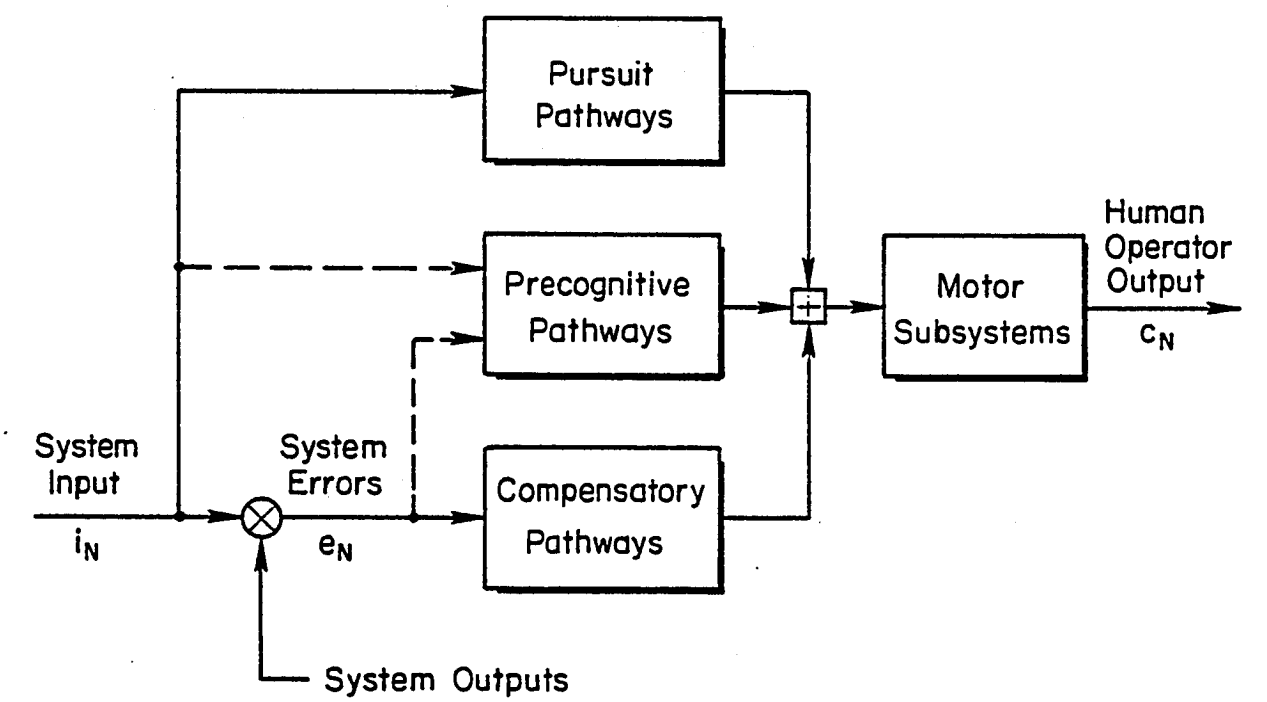


Figure 9. Three Modes of Perceptually Centered Model of Human Behavior — Subsystem for Nth Human Element

TABLE 5

SUMMARY CHARACTERISTICS OF PATHWAYS IN PERCEPTUALLY CENTERED MODEL OF HUMAN BEHAVIOR

PATHWAYS SELECTED	PERCEPTUAL FIELD CONTENT	ACTION OR OUTPUT	CORRELATES OF TRANSITION AMONG LEVELS OF SOP
Compensatory	Narrow; deviations only	Designed to correct exceedences and reversals; not necessarily rehearsed	Expanding perceptual field content and extension thereof ↓ Increasing time delay ↑ Increasing bandwidth ↓ Increasing rehearsal ↓ Increasing perceptual motor load ↑
Pursuit	Broader; separable inputs, outputs, commands, disturbances in addition to deviations	Designed to correct deviations and to compensate for internal delay; moderately well rehearsed	
Precognitive	Exceedingly broad and extended, even among other individuals and organizations by means of a conference, by recall of past experience, or by recruitment of other resources; separable inputs, outputs, commands, disturbances only; feedbacks not necessary	Discrete; cued, transient; very well rehearsed	

In the context established by all of the discussions thus far we can now give a definition of what we mean by "perception" as the summation of sensory input (exogenous and endogenous signals) which arrives at the individual or collective attentional level and the subsequent selection and integration of signals from this field into pertinent constructs.

B. THE SUCCESSIVE ORGANIZATION OF PERCEPTION THEORY FOR SKILL DEVELOPMENT

In what has gone before, we have emphasized that much of human behavior can be characterized as input/output operations using one or more of the three basic pathways. At this point we wish to use the same behavioral descriptors as components of a theory of learning. This also derives from manual control, but has a generality which transcends those peculiar circumstances (Refs. 2, 3, 5, 22, 23). The Successive Organization of Perception theory describes the human operator's synthesis, by means of internal organizational modifications derived from training/experience, of progressive arrangements (selections) within the total potential perceptual field which:

1) Is equivalent to more elaborate displays (or sources in general) than those from which the stimuli were obtained.

2) Induces references or backgrounds which are not physically present among the sources of the stimuli.

3) Makes highly efficient use of any coherence or pattern in the presented stimuli.

As a paradigm for skill development, the SOP theory explains the development of skill as a progression from compensatory through pursuit to precognitive stages — or, in other words, a progression from behavior patterns which exhibit closed-loop, to combined open- and closed-loop, to purely open-loop properties. There are, of course, conditions (e.g., compensatory displays with random inputs and disturbances) where the skill cannot develop past the compensatory stage. On the other hand, in many conditions, especially with discrete inputs, it is possible to go all the way from an effective compensatory situation with its

relatively low system bandwidth to an effective precognitive condition with maximum bandwidth. In the simplest of terms, the Successive Organization of Perception theory is intended to explain the commonly observed characteristic of complex psychomotor skill development in which there is a progression from an instant by instant conscious perceptual motor action to a rapidly executed subroutine triggered by a single command.

The SOP theory leads to an understanding of both progressive and regressive control and monitoring behavior during training, transfer, rehearsal, and stressful operations. It can also be associated with at least one concept of perceptual motor loading.

There is, as yet, no unique and agreed-upon definition of pilot or controller workload, because of the incommensurate dimensions of various loading factors in a complex task and the lack of any cohesive theory or models. For example, there is now no index suitable to represent the perceptual-motor load due to perception of sensory inputs from different modalities (vestibular and/or visual), and of cognitive mental loads versus pure sensory-motor loads (failure management versus multiaxis control) even for well-practiced stable conditions.

In our concept of the perceptual-motor loading components of pilot workload, perceptual-motor activity is carefully defined to involve only conscious perceptions and actions. For example, we would not class sleepwalking as a perceptual-motor load. It is handling the unpredictable (emergency) or unfamiliar (lack of practice) which taxes the operator's workload capacity. In this context the three stages of SOP can be compared on a perceptual-motor load (PML) basis.

1. Initial stage (compensatory control). The early phases of learning predominantly involve continuous, conscious activity. We would, therefore, expect a high PML during compensatory control.
2. Intermediate stage (pursuit control). A considerable portion of the controller's output results from execution of prelearned responses to discrete cues in the input (e.g., axis crossings for sine wave tracking). Compensatory control activity, although present, experimentally shows a regression. This implies a lower sensory-motor activity level. Therefore we would expect the pursuit level of operation to have a lower PML than the compensatory stage.

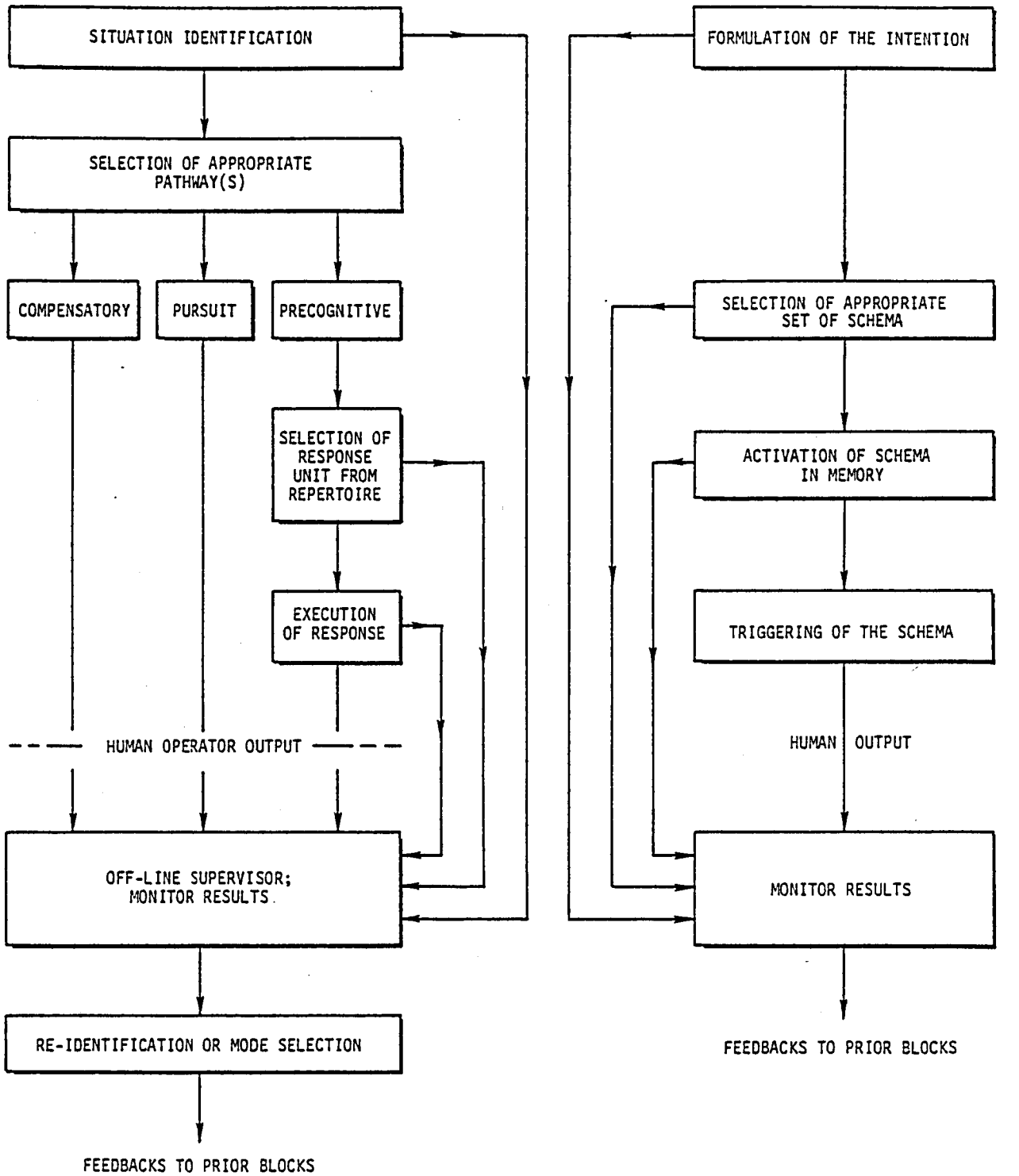
3. Final stage (precognitive control). At this level of skill most of the operator's output consists of execution of stored commands, and his conscious perceptual activity is mainly concerned with decision-making activity. This should result in a lower PML for a given control task.

Pilots indicate (Ref. 24) that one effect of noncurrency is a general roughness of control application and lack of precision. This causes them to spend more time on controlling the aircraft (higher workload), which leaves less time for other procedural matters involved in complex tasks. This degradation of control skill corresponds to regression on the SOP control skill scale given above. Thus, lack of practice on a skill increases the perceptual motor loading of that skill, resulting in less workload reserve capacity for other elements of a complex task. It is apparent that lack of practice could reduce this capacity to less than that required for carrying out the remaining elements of a complex task, or a simple emergency could arise that would consume additional capacity, thus overloading the pilot and resulting in degraded system performance, if not failure.

One further pertinent pilot comment relevant to pilot workload is that experience reduces the effect of lack of practice. In other words, the more experienced pilot can tolerate a greater lack of practice. This observation has implications for training protocols in that the intensity and length of training should depend on the individual experience level.

Table 5 includes perceptual motor load and rehearsal as correlates of transitions among the levels of SOP.

The compensatory-pursuit- precognitive pathways structure is suitable to represent not only a pilot or controller's progression to, or regression from, higher levels of internal cognitive system organization in a given situation, but also grossly to represent the possible loop structures when different levels of display information are provided. In addition, the process can even describe the procedural organization and operating discipline among individuals on the flight deck or within the air traffic control system.



a) Simplified Metacontroller for Successive Organization of Perception

b) "Theory of Action," Ref. 32

Figure 10. Flow Diagram for SOP Operations and the Ref. 32 Theory of Action

C. INTEGRATION OF THE PATHWAYS — THE METACONTROLLER

Each level of organization contains a number of subsets of behavior appropriate to the task. Assume that identifiable prerequisite conditions and limits can be found (e.g., experimentally) for each subset mode of observed behavior. Then one model for the perceptual organization process would be an active off-line supervisory monitor which identifies the conditions that currently exist, selects and activates some most likely mode (pathway), monitors the result, reselects a new mode when necessary or when further information is identified as a result of the first operations, and so forth. Appropriately, this has been termed the metacontrol* system in Ref. 25. A simplified diagram of such a metacontroller is given in Fig. 10a. Other preliminary work on an algorithmic-type model for the SOP process is given in Ref. 5. The possibilities for error due to inappropriate actions within such a system are manifold. Such a model provides a logical basis for understanding some of the causes underlying selection of an inappropriate behavioral mode which may ultimately lead to an identifiable error.

As indicated in Fig. 10a, an appropriate form for this model is a flow or decision process algorithm. Related models have been described in Refs. 26 and 27, and applied to a specified task involving a given sequence of subtasks in Refs. 28 through 31. Thus, the algorithmic approach is by no means novel. Most of these attempts have had limited application because of the inordinate complexity and repetitive cycling required to represent continuous tasks. Yet by breaking out the compensatory and pursuit pathways as separate entities which handle most of the continuous operations, the metacontroller of Fig. 10a gets around

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*Metacontrol = the human's activity-supervising control, transcending the various directly involved systems such as the perceptual, central, and neuromuscular systems (from Greek "meta" meaning "involved with changes").

some of these problems. Continuing research in the disciplines of observation, pattern recognition, estimation, and timeshared processing should yield additional material useful to the interpretation of SOP. For example, Table 6 presents the summary of a sequential pattern perception and recognition theory from Ref. 36 together with some remarks and connections with SOP and other models which have been found useful in characterizing human behavior.

A particularly interesting parallel to the SOP metacontroller which is especially valuable for the understanding of error is given in Ref. 32. The "Theory of Action" proposed there has a number of cognitive stages and components. The base stores for action are organized memory units or sensori-motor knowledge structures — "schemas" which control skilled action sequences. A basic control sequence starts with intention, and proceeds through selection, activation and triggering of schema to result in an output action. The results at various levels in this sequence are monitored, and may be modified by feedbacks to the previous stages. A simplified block diagram for this theory is shown in Fig. 10b. It clearly has many similar features to the metacontroller of Fig. 10a, particularly with the precognitive features. Much of the Fig. 10b model is based on the study of verbal "slips," which can be errors by another name, so the connections between human manual control and verbal activities are very useful in our search for generalization.

The suggestion here is that algorithmic models may be appropriately and successfully applied to describe the SOP sequence itself. Most of the observed manual control behavior falls into relatively few categories from which logical criteria can select the most suitable, e.g., the three phases of perceptual organization in Figs. 1 or 9. Within these phases, various submodes are required, but many of these already have well-modeled characteristics and extensive data bases. The rather heterogeneous forms and degree of approximation described here and elsewhere are ideally called up by mode selection algorithms. Thus, algorithmic models are used where they are best suited (logical functions), while isomorphic models of human behavior are used where they are most efficient (well-defined tracking or stimulus-response situations).

TABLE 6

SUMMARY OF A SEQUENTIAL PATTERN PERCEPTION THEORY

SUMMARY OF A SEQUENTIAL PATTERN PERCEPTION CENTERED AND RECOGNITION THEORY (Ref. 36)	REMARKS AND CONNECTIONS WITH PERCEPTUAL CENTERED AND OTHER MODELS
1) Memorizing a pattern is the process of constructing an internal representation of the pattern in memory, in the form of a sequential feature network, a closed network of memory traces recording the features of the pattern and the attention shifts required to pass from feature to feature across the visual field.	1) Closed cyclic nature of feature network.
2) Recognizing a pattern is the process of finding in memory a feature network which matches the pattern, the matching being carried out sequentially feature by feature.	2) Closed-loop process of recognition; "matching" proceeds at the compensatory level in the most unfamiliar situations.
3) The attention shifts from feature to feature may take the form of saccadic eye movements or of internal attention shifts, according to the angular displacement involved.	3) Consistent with Sanders' findings, (Ref. 37); internal attention shifts proceed at neural speeds.
4) During recognition the matching process is guided by the feature network, which directs attention from feature to feature of the pattern.	4) "Matching" is aided by short-term memory which is consistent with Sperling's findings (Ref. 38); peripheral vision may also guide the matching process at the pursuit-level in more familiar situations.
5) The directed nature of the matching process (noted in 4) is the key to the recognition of patterns in the presence of noise and clutter. The feature network directs attention to the features of the pattern, while avoiding the noise and clutter.	5) Consistent with Mackworth's findings that visual noise causes tunnel vision (Ref. 39).
6) Memorizing and recognizing a pattern are seen to be closely analogous to memorizing and repeating a conventional sequence of behavior, each being an alternating sequence of sensory and motor activities.	6) Consistent with SOP.
7) Thus habit produces the scan-path, a habitually preferred path followed from feature to feature through the feature network and, correspondingly, across the visual field. This path differs from person to person and from pattern to pattern, but is fixed and characteristic for a given person viewing a given pattern.	7) Characterized by great determinism.
8) Under conditions in which attention shifts must take the form of eye movements, the development of the scan-path during memorization of a pattern has been experimentally demonstrated. Its use in subsequent recognition awaits confirmation.	8) Contrast these findings with the apparent lack of determinism in instrument scanning under IFR reported in Ref. 14 and Ref. 40 and their antecedents.

D. AIDS TO PROGRESSION WITHIN THE SUCCESSIVE ORGANIZATION OF PERCEPTION PROCESS

Various levels of possible skill reinforcement and required aids are given in Table 7. The required level and aid depends on the nature of a given task and its criticality as to what level of skill proficiency is required. Rehearsal would seem to be adequate for procedural tasks, and various visual aids should be provided for review of procedures. There are indications that rehearsal is appropriate to other tasks as well. In an informal STI survey (Ref. 33) the pilots questioned indicated that they may mentally review the procedural sequence of a complex task such as approach and landing when they feel noncurrent. On a different task Espenshade (Ref. 34) found that performance improvement on a ball-throwing task by blindfolded subjects resulted from a clean concept of the task (rehearsal) rather than an awareness of movement (perceptual-motor practice)! Finally, in our experience at STI in training naive

TABLE 7

LEVELS OF REINFORCEMENT

LEVEL	AIDS
Rehearsal	Procedural list
	Other visual aids; graphs, charts, etc.
Synthetic practice	Psychomotor skill tester
	Panel, display mockup with moving controls
Part task practice	Part task simulator
	Actual controls and displays with capability of presenting practice task
Actual task practice	Actual controls and displays with capability of presenting practice task

subjects on complex vehicle control dynamics we have found that a brief description of control strategy (rehearsal) causes a significant initial increment in performance improvement over naive, unrehearsed subjects. Thus, it appears that rehearsal is applicable even to complex psychomotor tasks.

The last three categories in Table 7 pertain to actual practice. The differences among them lie in the degree of fidelity with which they represent the actual task. Synthetic practice refers to the reinforcement of basic behavioral or skill factors. We believe that for certain classes of tasks this type of practice may be adequate. For example, a roll-rate-limited sidestep maneuver for collision avoidance requires time-optimal control of vehicle dynamics which can be approximated by three integrators in series [in Laplace transform notation, $Y_c(s) = K/s^3$]. The control of these dynamics is extremely difficult and performance is quite sensitive to lack of practice. The behavioral skill factor critical to this task is the ability to compensate for two of the integrations (double lead equalization in manual control terminology) and practice on a synthetic task would probably suffice to maintain the required skill level on this task.

Part task practice may be required for skills particular to the specific details of a complex task such as vectoring or approach and landing.

Finally, actual task practice may be required for complex terminal area control tasks where required skills and skill levels are intimately involved with details of the real task.

A further question that must be considered in regard to skill reinforcement is the degree of practice or rehearsal required. One important factor here is the temporal relationship between the reinforcement and actual task performance. In our laboratory we have found that with some simple control tasks, previously trained subjects require only a warmup period directly prior to task performance. For more difficult tasks a previous practice or retraining session is required, and for very complex tasks a series of retraining sessions is required. For

complex tasks we have found that only a given level of training or retraining can be accomplished in a given session and that the retraining program must extend over several separate sessions.

E. BUILDUP OF MISSION PHASE BEHAVIOR SEQUENCE(S) FROM CONSTITUENT TASK BEHAVIOR

For a particular task the human component(s) as input-output elements consist of one (or more) of the pathways illustrated by Fig. 9. The human's operations are thus defined as an open-loop, closed-loop, or open- and closed-loop behavior pattern with identified sensory input and motor output modalities. For some inputs, of course, there is no immediate output; instead, the information received may simply be stored in memory. In other cases the lack of a measurable output should nonetheless be interpreted as the 0 portion of a 0,1 binary pair of possibilities.

To apply these elementary behavioral models to complex operations of men and machines, they must be associated with sequences of operations which, together, serve to accomplish a desirable end, i.e., a mission. To accomplish this the mission is first defined and partitioned into a hierarchy of constituents. The primary constituents are mission phases. These are of a size and duration which allow the broadest factors (e.g., environmental variables) that influence human behavior to be identified. At the next level are tasks, which are associated with a particular operation in a sequence and are sized to permit the identification of "critical" skills. Aberrations in the execution of these skills ultimately determine the sources of contributions to human error.

A mission phase may be broken down into various subdivisions depending on its complexity. For our purposes here we are ultimately interested in the elemental unit of all phases involving the human operator, the task. As a working definition here we will define a task as an activity at the functional interface of the human operator and the objects and environments with which he interacts (adapted from Ref. 35). We will further specify a task for our purposes here as a goal or criterion-oriented work

increment involving application of a skill or set of skills by the human operator. Thus, by partitioning the mission phases into tasks, we can then identify those fundamental human operator behavioral factors, skills, which influence flight safety. For tasks which are critical to flight safety (i.e., exert a predominant influence in some sense), it is the proficiency with which a skill or set of skills is applied that we wish to consider in order to identify the underlying sources of human error.

To illustrate these remarks, Table 8 and its companion Fig. 11 present an exemplary task breakdown for the pre-approach, approach, and landing mission phases of a Category 1 or 2 instrument approach. The tasks include checklists, tuning radios, requesting and receiving clearances, navigating as required by ATC procedures, etc., as well as flying the airplane. Each task is listed as an item in an ordered, nominal sequence. Conceivably this order might be changed or omitted in off-nominal circumstances, and this by itself may be a cause of error. Otherwise, no consequence of an erroneous execution of a task is explicitly indicated on the list.

Associated with each task are input and output modalities for the pilot (or other active crewmember). And, finally, with each task is an indication of the human behavior characteristics nominally involved in carrying out the task at hand. In many cases the nominal behavioral characteristics may not be exhibited by actual crews, and this abnormal behavior may result in an out of tolerance system error.

In most of the tasks where precognitive operations are cited in Table 8 as nominal or customary additional qualification is necessary. Such open-loop operations are normally of limited duration and are properly interspersed or concluded with closed-loop operations either directly, as in dual mode continuous control, or indirectly in the context of the off-line supervisory monitor shown in Fig. 10a. Omission of the closed-loop monitoring activity may in fact lead to human error as shown in Ref. 37. Examples are: tuning communications, navigation and identification (CNI) equipment, selecting partial flaps, lowering gear, setting throttles, dumping fuel, and accepting ATC clearances which are either physically

TABLE 8

MISSION PHASE, TASK, AND HUMAN ELEMENT OPERATIONS BREAKDOWN FOR APPROACH AND LANDING

PHASE OF FLIGHT	LOCATION ON FIGURE	TASKS	MODALITIES	NORMAL OPERATIONS
Preliminary preparations for approach	A	Request/receive approach clearance	Verbal/Verbal	Precognitive
		Complete preliminary before-landing checklist	Visual/Manual/Store	Precognitive; compensatory
		Check that all systems are operating (no flags)	Visual - Store	
		Tune and identify navigation receivers to ILS	Visual/Manual	Pursuit
		Tune and identify ADF's to LOM (LMM)	Visual/Manual	Pursuit
		Preselect and enter subsequent communications frequencies	Visual/Manual	Precognitive (if switchboard)
		Set marker beacon switches and test	Visual/Manual	Precognitive; compensatory
		Set decision height on radio altimeter	Visual/Manual	Pursuit
		Set inbound ILS localizer heading on respective course indicators	Visual/Manual	Pursuit
		Maneuver to proceed to final approach fix	Visual/Manual	Precognitive; compensatory
Initiation of lateral guidance acquisition	B	Maintain altitude	Visual/Manual	Compensatory
		If procedure turn required select appropriate heading	Visual-Store	
		Accomplish procedure turn	Visual/Manual	Precognitive; compensatory
		Report procedure turn inbound	Verbal	
Preparations for acquiring vertical guidance	C	Acquire initial approach airspeed	Visual/Manual	Pursuit
		Set partial flaps	Visual/Manual	Precognitive; pursuit
	D-E	Descend to (and maintain) initial approach altitude	Visual/Manual	Pursuit
	E	Set speed command system to desired speed	Visual/Manual	Precognitive; pursuit
		Increase flaps and reduce speed	Visual/Manual	Precognitive; compensatory
		Check missed approach procedure, decision height, and RVR	Visual - Store	
Acquisition of lateral guidance	F	Initiate capture of localizer beam	Visual/Manual	Precognitive
	G-J	Stabilize on lateral flight path	Visual/Manual	Compensatory
	G-Q	Maintain lateral guidance	Visual/Manual	Compensatory
Acquisition of vertical guidance and completion of preparations for landing	H	Lower landing gear	Visual/Manual	Precognitive; compensatory
	I	Lower nose flaps and start bleeding more airspeed	Visual/Manual	Precognitive; compensatory
	J	Check time at outer marker	Visual - Store	
		Capture glide slope beam - extend full flaps, acquire final approach airspeed, and establish sink rate	Visual/Manual	Pursuit
		With safe landing gear indication, complete "final checklist"	Visual/Manual/Store	Precognitive; compensatory
		Change to tower frequency	Visual/Manual	Precognitive; pursuit
		Report OM inbound	Verbal	
	J-K	Stabilize on vertical flight path	Visual/Manual	Compensatory (DE); Pursuit (VE)
	J-M	Maintain vertical guidance	Visual/Manual	Compensatory (DE); Pursuit (VE)
Final approach	K-M	Maintain stabilized flight path (in all axes)	Visual/Manual	Compensatory (DE); Pursuit (VE)
	L-M	Use extended glide slope or Category II beam for vertical guidance	Visual/Manual	Compensatory
Decision Height	M	Execute missed approach if required	Visual/Manual	Precognitive; compensatory
Flare	M-P	Reduce sink rate	Visual/Manual	Precognitive; pursuit
	M-P	Decrab to align airplane with runway	Visual/Manual	Pursuit
Touchdown and rollout	P	Contact with ground	Motion, Visual - Store	
	P-Q	Steer throughout rollout	Visual/Manual	Pursuit
		Decelerate to a stop	Visual/Manual	Pursuit

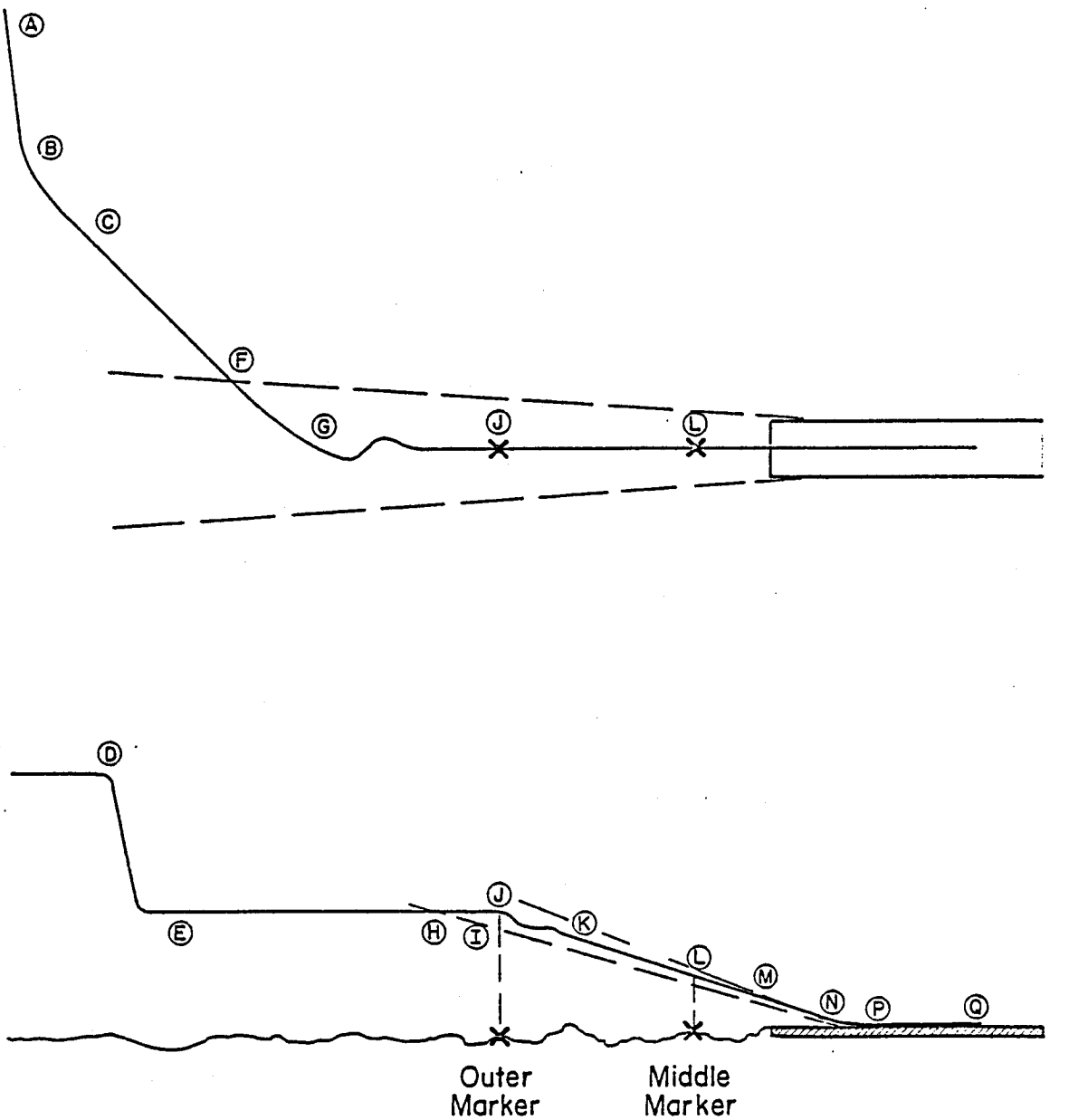

Figure 11. Sequence of Tasks Performed During Approach and Landing

impossible or unsafe. To emphasize this point, some of the precognitive operations in Table 8 are accompanied by compensatory operations. The nature of the control and display interface with CNI equipment in particular will also determine whether channel frequency selection can be purely precognitive or must include compensatory verification.

For the study of human error, the nominal task breakdown illustrated here must be further subdivided to account for all possible outcomes. This will be illustrated in Section V for the terminal end of the approach and landing mission phases. Other off-nominal aspects which should be considered are the accumulation of stress and degradation of skill. Each mission phase presents a combination of environmental and task stresses on the crew, and these stresses influence crew performance. After lapses in operational practice or in long duration flights, crew members have to cope with the problem of maintaining proficiency of skills which may be critical to flight safety. Skills performed infrequently prior to or during each flight, for whatever reason, are most likely to fall into this category. Of these skills, those having high workload factors by virtue of being time constrained or because they involve complex operations are most likely to cause serious performance decrements. Several conditions may contribute to the degradation of these skills:

1) Lack of practice.

2) Inability to practice in the appropriate environment.

3) Interference or negative transfer arising from the practice of competing skills.

4) Physiological deconditioning due to fatigue induced by the environment or due to alcohol or drug stresses.

The tasks which are most likely to be affected by these human conditions should be especially flagged.

Most of the points made above have an intuitive appeal as well as a logical structure. This overall structure has been outlined here to provide an example showing the tying-together of elements into a whole which

accomplishes the sequences necessary for mission success. It also provides a framework exemplifying the spatial-temporal facets of the mission phase event- or time-lines which are major features in the description and quantification of human (or automatic controller) operational action.

Using this overall structure as a point of departure, we progress in Section IV from a description of the normal to the abnormal, i.e., from satisfactory to unsatisfactory error performance. Again using this framework as a point of departure, we progress in Section V from a description of the single specific task behavior to a description of ensembles of behavior, i.e., from models of specific instances to probabilistic generalizations.

SECTION IV

CLASSIFICATION OF THE SOURCES AND DISTINGUISHING CHARACTERISTICS OF ERROR

A thorough evaluation of piloting and traffic controlling tasks among mission phases within the national airspace environment is a prerequisite for planning research on or conducting an investigation of human error which employs full mission simulation. The importance of this prerequisite has been emphasized by the example of the approach and landing tasks at the end of Section III. Having thus identified at least some of the potential for human error among normal operations, we turn our attention in this section to the abnormal — classification of the sources and distinguishing characteristics of error itself.

Another prerequisite for planning and conducting research in any discipline is a set of accepted definitions. For example, such terms as defect, failure, reliability, unscheduled maintenance, and performance measurement have acquired disciplined meaning where applied to purely machinelike systems. An analogous glossary of terms is not yet widely accepted for analysis of human reliability and performance. In the next topic, therefore, we shall adopt several definitions of error already proposed and qualify the meaning of others.

A. DEFINITIONS OF ERROR

As we have already remarked, errors or mismatches between desired and actual system or subsystem outputs are the sine qua non of situations where feedback is involved as an operating principle. Most of the time human operators use these errors to advantage in performing as error-correcting rather than error-avoiding system elements. For this reason in operations involving pilots, air crew, and ATC, the errors per se are of major concern only when they are undesirable because of their size, timing, or character. These errors, which are intolerable in one way or another, we shall call grievous errors.

In general, a grievous error will involve an exceedence of safe operating tolerances. "System error" and "system deviation," terms used by the FAA Air Traffic Control Service to describe procedural errors, missed acquisitions, and extreme deviations that lead to interactions between two aircraft, are grievous errors. These may derive from malfunctions or failures of system components which result in degraded system operation. Alternatively they may stem from the impact on a normally operating system of an unexpectedly severe forcing function or disturbance. This is an instance of what Singleton (Ref. 41) refers to as a substantive error, non-intended performance because the problem was inadequately defined at the outset, before the system requirements and specifications were established, or the system design itself was inadequate.

Singleton also introduces the term formal error to apply to cases where some rule has been broken. Grievous errors in general can be verified quantitatively because exceedences of tolerances can usually be measured. On the other hand, transgressions of a rule may not necessarily be observable or measurable, unless the rule specifies a commensurate tolerance. Out-of-sequence performance (within tolerances otherwise) is an example of transgression of a rule which might very likely be observable.

The substantive and formal error classifications are useful in setting up a taxonomy of human error definitions. In general human error ≡ inconsistency with a predetermined behavioral pattern used in establishing system requirements, specifications, and the resulting design (Ref. 42) and in defining the procedures to be used as well. Then,

1) Formal (human) error ≡ transgression of a rule, regulation, algorithm (Refs. 41 and 43), or out-of-sequence performance (Ref. 44).

2) Incoherent (human) error ≡ non-required performance, i.e., output not stimulated by an input (Ref. 44).

3) Substantive (human) error ≡ non-intended performance, e.g., because the procedure was inadequately defined.

Human errors that do not always result in grievous errors may be nearly impossible to measure in practice unless behavioral identification techniques

are employed. Behavioral identification may be performed by qualified observers (Refs. 24, 45, and 46) or by signal correlation analysis which can partition human error into coherent and incoherent components. Such identification of human errors which may be inconspicuous in one situation is very important, for they may lead to grievous errors in other circumstances.

B. SOURCES AND CAUSES OF HUMAN ERROR

The functional pathway triad and metacontroller model for human behavior developed in Section III contains within its structure many features which can, in abnormal versions, lead to grievous system errors. These features we shall refer to as sources or antecedents of error. Sources are endogenous or internal to the human. Their consequences are all measurable in terms of changes from ideal or nominal human behavior for a particular task. These changes may be induced by external (exogenous) factors which will be referred to as causes of error. The first two columns of Table 9 illustrate these distinctions for compensatory operations.

The remaining two columns of Table 9 present a verbal synthesis of a great deal of empirical data from many experimenters. All of the currently demonstrated forms of abnormal compensatory input-output behavior are represented here. In total they represent an error source which can be described generally as

> inappropriate perception, decision, and/or execution within a selected level (in this case, compensatory) of organization of behavior.

The sources of error in this framework are summarized in Table 10.

In principle tables similar to Table 9 can be constructed for the other source possibilities in Table 10, e.g., Table 11 for pursuit operations. However the experimental data base for most of these is nowhere near as comprehensive as it is for the compensatory pathway. Many of the elements in the precognitive pathway can be developed, by analogy, from Table 1 of Ref. 32, which lists the presumed sources of "slips" (or errors) in the structure of Fig. 10b.

TABLE 9

BEHAVIORAL SOURCES OF ERROR IN COMPENSATORY SYSTEMS

SINGLE CHANNEL OPERATIONS

BASIC SOURCE (ENDOGENOUS)	CAUSES (EXOGENOUS)	OPERATOR BEHAVIOR	EFFECTS ON SYSTEM
Extreme command or disturbance amplitudes	Unexpectedly large command or extreme environment	Operator response normal	System overloaded, forced out of tolerance although operating properly
Extreme command or disturbance bandwidth	Broadband input signal noise; Unexpectedly broadband disturbance	Regression of crossover frequency	Reduced system bandwidth
Controlled-element change	Mulfunction/failure in controlled element	Affecting output for transient interval; Adaptation to new controlled element	Transient errors during transition; Reduced system bandwidth
Reduced attention field	Poor signal/noise ratio (e.g., poor contrast, high intensity distraction stimuli, low level signals, etc.)	Operator threshold, net gain reduction	System bandwidth reduction; (missed signals as one extreme)
Reversals	Misperception of error sign; Naivete	Remnant increase; Intermittently reversed output	Increased system noise; Intermittently reversed system output

MULTI-INPUT OPERATIONS

BASIC SOURCE (ENDOGENOUS)	CAUSES (EXOGENOUS)	OPERATOR BEHAVIOR	EFFECTS ON SYSTEM
Divided attention, perceptual scanning	Increased informational requirements for monitoring or control	Remnant increase (scanning); Increase in loop gains; Simultaneous multi-channel operations	Increased system noise; Reduced bandwidth
	Information overload: Too many separate input channels; Too many significant signals; Backlog of unattended operations	As above, plus failure to detect some signals, increased latencies, and missed output responses	Saturation; Missed responses; Instability in the mean square sense
Reduced attentional field	Operator impairment (fatigue, alcohol, hypoxia, etc.)	Remnant increase over scanning; Further decrease in loop gain; Sequentially-switched single channel operations; Deletion/missed responses	Increased system noise Reduced bandwidths Increased latencies Missed responses
Illusions, kinetosis	Conflict between or among visual, vestibular, aural, kinesthetic and/or proprioceptive inputs	Remnant increase; Decrease in operator's gain; Mal à propos responses; Missed responses	Increased system noise Reduced bandwidth Mal à propos responses Missed responses

TABLE 10

SOURCES OF HUMAN ERROR

(Sources are endogenous or internal to the human operator by definition)

- Inappropriate perception, decision, and/or execution within a selected level of behavioral organization
  - Compensatory (expanded in Table 9)
  - Pursuit (expanded in Table 11)
  - Precognitive (expanded in Table 1 of Ref. 32)
    - Selection of response unit
    - Execution of response
- Transitions from a higher to lower level of behavioral organization
  - Precognitive to pursuit
  - Precognitive to compensatory
  - Pursuit to compensatory
- Inappropriate organization of perception and behavior for the task at the executive level of the metacontroller
  - (Expanded in Table 12 for the cockpit environment)
  - (Expanded in Table 13 for the traffic control environment)
- Inadequate off-line monitor/supervisor in the metacontroller

TABLE 11

BEHAVIORAL SOURCES OF ERROR IN PURSUIT OPERATIONS

(Multi-Input Operations, by Definition)

BASIC SOURCE (ENDOGENOUS)	CAUSES (EXOGENOUS)	OPERATOR BEHAVIOR	EFFECTS ON SYSTEM
Controlled element change	(see corresponding causes in Table 9)	Transient regression to compensatory level (see corresponding behavior in Table 9)	Transient errors during transition; Reduced system bandwidth
Divided attention, perceptual scanning	(see corresponding causes in Table 9)	Remnant increase; Decrease in operator's gain; (see also corresponding behavior in Table 9)	Increased system noise; Reduced bandwidth; (see also corresponding effects in Table 9)
Reduced attentional field in spatial dimensions	Poor input and/or error signal/noise ratio (e.g., inability to identify input.) Task involves disturbance regulation rather than command-following and disturbance cannot be identified; Mismatched scaling between input and error; Distortion of input; Lack of input conformability with visual field; See also corresponding causes in Table 9	Remnant increase; Operator's threshold on input may cause missed responses and regression to compensatory level; Operator's threshold on error may reduce gain in or open compensatory loop (see also corresponding behavior in Table 9)	Increased system noise; Reduced system bandwidth (missed responses as one extreme)
Reduced attentional field in temporal dimension, i.e., reduced preview	Inability to identify <u>future</u> input or disturbance; Prodigious extrapolation required to estimate <u>future</u> input or disturbance	As above, plus increased latencies	As above, plus increased response latencies
Reversals	Perceptual inversion of input; Faulty input-background discrimination; Lack of input conformability with visual field	Remnant increase; Intermittently reversed output	Increased system noise; Intermittently reversed output
Illusions, kinetosis	(see corresponding causes in Table 9)	Remnant increase; Decrease in operator's gain; Mal à propos responses; Missed responses	Increased system noise; Reduced bandwidth; Mal à propos responses; Missed responses

TABLE 12

CAUSES OF ERROR LEADING TO INAPPROPRIATE ORGANIZATION OF PERCEPTION AND BEHAVIOR AT THE EXECUTIVE LEVEL OF THE METACONTROLLER IN THE COCKPIT ENVIRONMENT

Items 1-5 are associated with the "situation identification" block in Fig. 10a

Item 6 is associated with the "selection of appropriate pathway(s)" in Fig. 10a

Errors in:

(1) Formulation of intent, assignment of function (to crew member by captain) and its priority

- Tactical Decisions (assignment retained by captain with rare exceptions)
- CNI
- Systems Operation
- Flight Control

(2) Identification of specific task/situation/action: <u>continuous</u> or <u>discrete</u>

- Information retrieval (e.g., checklists, clearance, instructions, manuals, maps, SIDs, STARs, approach plates)
- Conferring to arrive at a decision
- Monitoring
- Controlling/commanding
- Command-Interpretation and transcription (e.g., clearance, etc.)
- Command-following (e.g., flying)
- Disturbance regulation
- Deferring action (changing priority)
- Reassignment of action (to a different crew member by captain)

(3a) Selection of likely sources of information and their temporal order (i.e., stale, current, or preview)

- Checklists, clearances, instructions, manuals, maps, SIDs, STARs, approach plates
- Voice advisory or command
- Visual field
- Relevant instruments/displays/annunicators
- Motion cues
- Proprioceptive cues

(continued on next page)

TABLE 12 (Concluded)

Errors in:

(3b) Assignment of priority in sources of information among inputs, feedbacks

Specific IFR sources
Specific VFR sources
Type of display: compensatory, pursuit, preview

(4) Identifying predictability or coherence in and among sources of information

Patterns in random commands, disturbances - nil
Patterns in wind shears - may be highly correlated
Patterns in programmed commands, maneuvers
Patterns in periodic commands, disturbances
Patterns in discrete commands, disturbances, failures
Patterns in slowly divergent or ramp-like disturbances, failures

(5) Identifying familiarity with task

Nil
Slight
Moderate
Great, i.e., very well rehearsed

(6) Organizing operation on inputs, feedbacks:

Continuous or discrete operations
SOP level: compensatory, pursuit, precognitive, combinations
Loop structure
Behavioral adaptation within loop structure
Specific cued (behavioral) programs

TABLE 13

CAUSES OF ERROR LEADING TO INAPPROPRIATE ORGANIZATION OF PERCEPTION AND BEHAVIOR AT THE EXECUTIVE LEVEL OF THE METACONTROLLER IN THE TRAFFIC CONTROL ENVIRONMENT

Items 1-5 are associated with the "situation identification" block in Fig. 10a

Item 6 is associated with the "selection of appropriate pathway(s)" in Fig. 10a

Errors in:

(1) Formulation of intent, assignment of function (to specialist by supervisor) and its priority

ATC: Enroute, terminal (departure, approach), final, surface

Commercial: Aircraft dispatcher, ramp control supervisor, area operations supervisor, operations controller

(2) Identification of specific task/situation/action: <u>continuous</u> or <u>discrete</u>

Information retrieval
Communication input
Conferring to arrive at a decision
Surveillance, searching, pattern recognition
Monitoring
Tracking
Controlling/commanding/advising/interrogating (communication output)
Deferring action
Reassignment of action (to a different specialist)

(3a) Selection of likely sources of information and their temporal order (i.e., stale, current, or preview)

Visual: Flight progress posting strips/ETABS
PPI/ATCRBS/DABS

Aural communications

(3b) Assignment of priority in sources of information among inputs, feedbacks

Specific visual sources
Specific aural sources
Type of display: compensatory, pursuit, preview

(continued on next page)

TABLE 13 (Concluded)

Errors in:

(4) Identifying predictability or coherence in and among sources of information

- Patterns in programmed tracks on PPI
- Patterns in predicted courses on PPI
- Patterns in programmed altitude responses
- Patterns in predicted altitude responses
- Patterns in overall flight progress
- Patterns in discrete commands, disturbances, failures
- Patterns in slowly divergent or ramp-like disturbances, failures
- Coherence in aural communications
- Interference in aural communications

(5) Identifying familiarity with task

- Nil
- Slight
- Moderate
- Great, i.e., very well rehearsed

(6) Organizing operation on inputs, feedbacks

- Continuous or discrete operations
- SOP level: compensatory, pursuit, precognitive, combinations
- Loop structure
- Behavioral adaptation within loop structure
- Specific cued (behavioral) programs (e.g., conflict alert and collision avoidance command)

Transitions from higher to lower levels occur when the attentional field becomes too narrow. They can also occur when the human is sufficiently impaired perceptually (i.e., by alcohol, fatigue, hypoxia, etc.) so that action as a multi-channel operator is significantly degraded. In these instances divided attention is possible only by switching to and fro as an essentially single channel information processing device.

Although probably one of the most fundamental sources of human error, the inappropriate organization of perception and behavior for the task at the executive level of the metacontroller has received much less attention in the literature than have inappropriate perception, decision, and/or execution within a selected level of behavioral organization. The SOP theory described in Section III offers a unifying approach to inappropriate organization as a source of human error. To illustrate this source more specifically, we have partitioned possible causes of error leading to inappropriate organization of perception and behavior in two contexts, the cockpit environment and the traffic control environment. (There are actually two traffic control environments, one operated by the Federal Aviation Administration, the other, peculiar to each commercial operator. For the purpose of classifying these causes of error among traffic controllers, however, one list will suffice; the other list will serve the cockpit.) Table 12 presents the partition for the cockpit, and Table 13, for the traffic control environment. Within each subdivision, specific examples are listed to help in understanding the meaning of the subdivision.

This concludes our subdivision of the causes of error. Next we shall consider the assignment of causes and some remedial actions.

C. ATTRIBUTION OF ERROR (ASSIGNMENT OF CAUSE OR RESPONSIBILITY FOR ERROR)

Singleton, in Ref. 41, identifies significant problems in addressing scientifically the issue of assigning responsibility for error.

> "Most societies have not resolved the distinction between two main approaches (to attribution). One assumes that human beings are responsible for their own actions and are therefore responsible for the errors they make. The opposite

> view is that errors are an inherent component in all human performance, that they should be planned for and designed for and when they do occur the fault should be traced to the system designer rather than the operator. At the individual level, few people are sufficiently self-confident to deliberately acknowledge their own mistakes, particularly if there are financial consequences in doing so. This is an especially difficult problem in the insurance world, where accidents are investigated with a view to deciding who is going to pay for the damage caused either to people or to property. In such a situation it is not surprising to find that it is impossible to regard the evidence as scientific in any sense."

One of the prime justifications for the study of full mission operations in the Man Vehicle Systems Research Facility is to avoid these problems gracefully. Another way is to sidestep the issue of attribution in order to acquire incipient and consummate error data with a semblance of scientific credibility. The NASA Aviation Safety Reporting System (Ref. 47) is a prime example of a confidential, non-punitive program designed to sidestep the issue of attribution in the process of acquiring a scientifically useful error data base.

Notwithstanding the aforementioned problems, we believe that there may be useful ways to classify the assignment of causes of error in an impersonal way which has scientific value. Such a classification is presented in Table 14. The subdivisions of attribution shown there were selected so that they could be identified with constructive remedial action. Examples of such remedies are listed on the right hand side of the table. Some of these, e.g., skill development and continuing rehearsal for proficiency maintenance, have been discussed thoroughly in Sections II and III.

TABLE 14

PARTITIONS OF ATTRIBUTION AND REMEDY

ATTRIBUTION Assignment of Causes of Error*	REMEDY Correction of Cause
• Inadequate definition of the problem at the outset before the system requirements and specifications were established. (Produces substantive or existential error, because the system specification itself is inadequate) otherwise called "unforeseen circumstances."	• Design modification
• Inadequate system design (presumes the specifications are adequate, but their interpretation in terms of the design is not adequate; therefore also produces substantive error.)	• Design modification
• Inadequate definition of the procedures (really part of system design, but emphasizes modus operandi and therefore also produces substantive error)	• Procedural modification
• Naiveté	• (Naiveté)
— Mismatched or misapplied skills.	— Selection and training for skill development
— Ignorance of regulations or rules	— Explanation and training
— Inadequate instruction of the procedures	— Retraining and rehearsal
• Inadequate interpretation and/or execution of the procedure(s)	• (Inadequate interpretation and/or execution of the procedure(s))
— Lapse in practice	— Continuing rehearsal for proficiency maintenance
— Psychophysiological stressors	— (Psychophysiological stressors)
(1) Workload	(1) Redistribution of some functions or tasks among crew members or reassignment of some functions to automatic control
(2) Environmental disorders	(2) Correction or reassignment
(3) Emotional disorders	(3) Reassignment, rehabilitation
(4) Alcohol, drugs	(4) Reassignment, rehabilitation
— Psychoneurosis	— Reassignment, rehabilitation
— Blunders — everyone involved thinks that everything is okay when it isn't.	— Requires an independent observer or agency to monitor, recognize, and correct.
— External disturbances (i.e., external to the human operator), e.g., wind shear potential traffic conflicts failures of the machine or system	— Design modification to sense the disturbance, if possible, so that the operator can adopt pursuit or precognitive levels of behavior to cope with the disturbance where the compensatory level is inappropriate; design modification to improve reliability of the machine, possibly even by reassignment of some functions to a human operator not otherwise overloaded.

* The absence of assignable cause means that the error will be called "chance" or "random."

SECTION V

MONITORING AND DECISION MAKING

With increased use of automatic controls and computers in modern day aircraft and traffic control systems, the role of the human operator is becoming more supervisory, involving increased amounts of monitoring and decision making. In these roles, human outputs are typically discrete (as opposed to continuous control actions) and include non-manual actions such as verbal communication. Monitoring and decision making errors can arise due to misperception of monitored information and misinterpretation of perceived information. Errors can also occur in the more cognitive aspects of decision making where the operator must account for various possible consequences of the alternative actions available to him.

Monitoring and decision making constructs and viewpoints are useful in full mission simulations with a complete crew in several ways. First, human errors sometimes appear to be inexplicable when, for example, only two courses of action are possible, and an operator appears to make the obviously wrong choice. By considering the elements of these task situations in a decision making context one can gain additional insight into the underlying factors involved. Second, if specific analytic decision-making models are reasonably appropriate descriptors of the mission phases being simulated, then the model can serve as a means for the analysis and interpretation of the experimental results. Third, a combination of monitoring, decision making, and control viewpoints is essential in treating repeated simulation runs by one crew, or an ensemble of simulations involving many crews. In a single run behavior and performance for all the tasks involved are specific concrete actions (or inactions), flowing in a sequence. Error is identified as an extreme deviation from a desired state. With many runs these concrete actions often exhibit differences, either in kind or in degrees. A probabilistic structure for particular events then becomes appropriate as a means of describing the experimental data. Further, the potential tradeoffs (based on experience and training) involved in selecting various emergency actions can be exposed in the light of a utility concept.

Monitoring and decision making theories are the appropriate vehicles for such considerations.

For simulations where a monitoring and decision making construct is likely to be useful the experimenter must recognize this potential at the outset by appropriately structuring the experimental tasks, scenarios, and performance measures. Then, when particular models for decision making are to be considered in data analysis, there may be further impact on the experimental design.

In the following discussion, monitoring and decision making are first presented from a conceptual point of view in order to identify the basic components of monitoring and decision making tasks that must be taken into account in simulation setup, selection of measurements, and experimental design. Analytical procedures for data analysis and modeling are then briefly covered. In the most general approach to studying monitoring and decision making behavior as discussed below, the detailed structure of the operator's task may not be clear so that only very general data analysis procedures can be applied with any certainty. As more is understood about the operator's behavior, certain assumptions may be invoked to allow more detailed analysis and perhaps modeling of the operator's task. This section is then concluded with an example to illustrate how a specific situation can be analyzed from a decision perspective to discover factors important in developing the appropriate experimental measurements to be made in a simulation.

A. GENERAL DECISION MAKING CONSTRUCT

Let us first consider the conceptual decision making construct of Fig. 12 , which includes the important aspects of a decision making scenario (general decision making constructs are discussed in Refs. 48-50). The conceptual construct involves (a) human operator(s)/decision maker(s) coupled to the controlled or supervised system and environment through input and output interfaces. Information is provided to the operator through visual, auditory, motion, and perhaps tactile displays. The decision maker's actions based on the displayed information are then transmitted to the system to change its state. This system might include

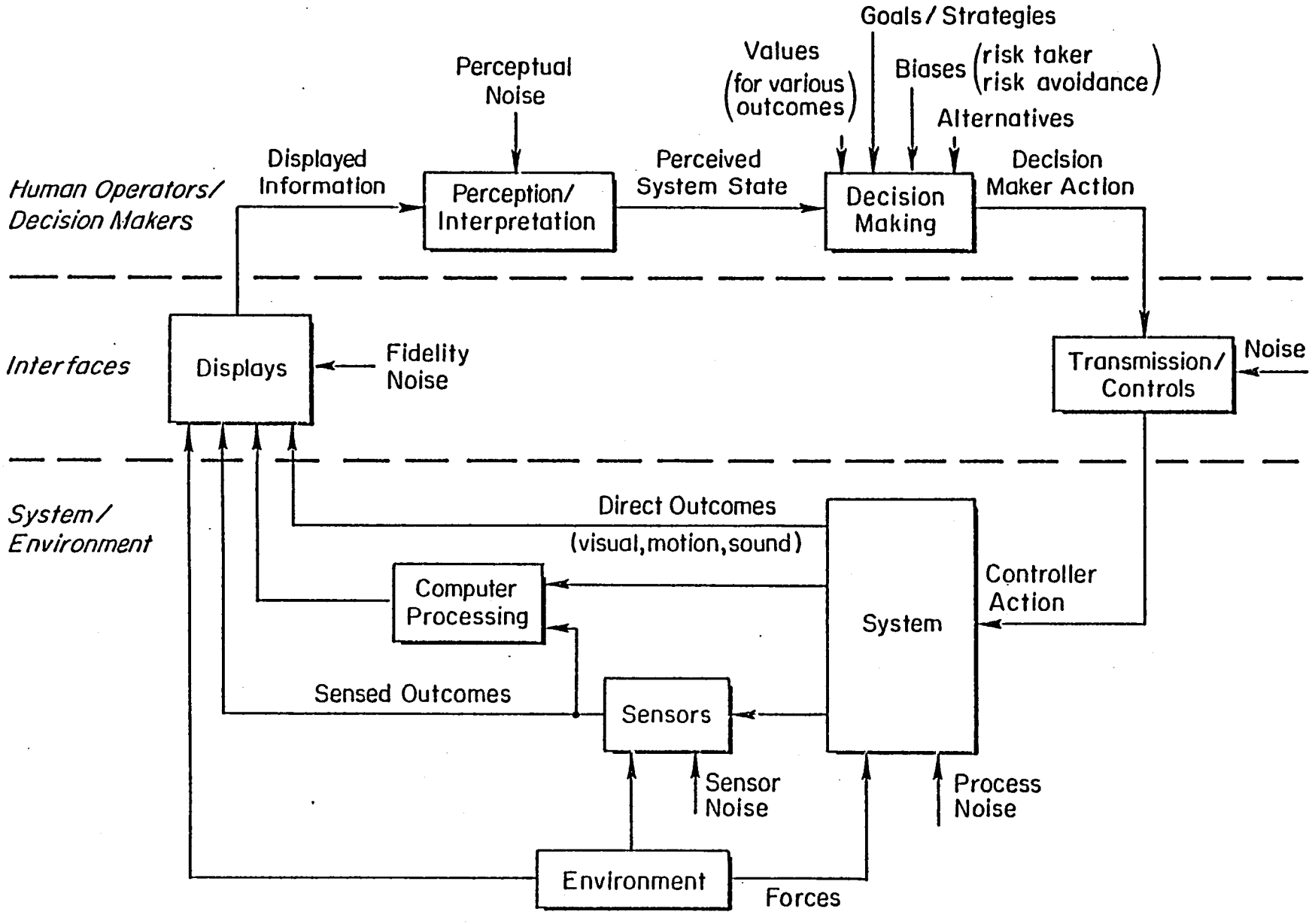

Figure 12. Conceptual Decision Making Construct

multiple operators and voice or telemetry links, and operate on single, independent decisions or multiple sequential decisions where one decision and action influences succeeding decisions (i.e., so called sequential or dynamic decision situations).

The input to decision making is provided by the operator's perception and interpretation of information on the displays he is monitoring. Displayed information might include real world visual, motion, and auditory feedbacks, plus raw and processed sensor data and higher level computer aiding information. At this input stage there is some possibility for misperception or misinterpretation of displayed data which is a source for human error in the decision making scenario. Perceptual noise has been studied in connection with driver decisions at signal lights (Ref. 51) and in gap acceptance (Ref. 52) and can be an important component in human decision making errors.

The perceived state of the system then provides an input to the decision making process as shown in Fig. 12, and is combined with various other inputs related to the operational scenario in which decisions are made. These other inputs are more difficult to measure in situ and may include 1) the possible alternative actions available to the operator(s)* which affect system response, 2) the potential consequences and associated utilities of the various alternative actions†, 3) the goals and strategies associated with a given operational scenario or mission, and 4) the biases of the individual decision maker(s) to take or avoid risk. Figure 12 emphasizes these other inputs even though each specific action from input

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* Alternative actions which are subjectively <u>believed</u> by an operator to be available may differ from those alternative actions which are intrinsically available.

† Utility assessment is the process of eliciting and estimating subjective human values for the outcomes of decisions. Reference 53 introduces the general problem of utility assessment and provides a technical review of the available techniques, models, and guidelines for using the procedures. Utility assessments of approach to landing are described in Ref. 54.

("displayed information") to output ("controller action") is accomplished using one or more of the triad of pathways described earlier.

Consideration of the above components in the decision making task is essential in the simulation and analysis of these situations. Many of these items are ingrained into the skilled (i.e., highly trained) human operator/ decision maker. However, the relative values used in making a decision are usually influenced by his state of mind, which, in turn, are affected by the fidelity of the simulation (i.e., realism).

The proper simulation of value (i.e., the worth or penalty) associated with the various system outcomes such as crashes, fuel or time loss, etc., is very important but difficult to achieve. For example the consequence of a crash to flight crew members in real life is serious injury or death, so extreme aversion to any action that might lead to this consequence is present. In a simulation then, some taboo or similar drastic structural penalty must be engendered into the crew by adjusting the experimental variables, instructions, and payoffs.

Again referring to Fig. 12, one sees that the decision maker's actions are transmitted to the physical system through some sort of interface which finally results in a direct control input to the system. The interface might include voice or telemetry links, which could provide a potential source of both noise and time delay affecting overall system operation.

The controller's actions change the system state along with potential process noise sources and other environmental influences. The state of the system is then displayed to the operator(s) in various ways. Some possibilities illustrated in Fig. 12 include directly observable outcomes via visual, motion, and auditory cues; sensor outputs which may include significant sensor noise; and higher levels of processed information which might include relatively sophisticated computer aiding.

The display interface with the operator provides the final transformation of information on the state of the system and environment. In the real world the display interface represents a design problem to provide complex arrays of information as simply and efficiently as possible in order to minimize operator reaction time and workload and to maximize the

quantity and quality of information transfer. In simulation a fidelity problem exists, particularly in recreating the motions, sounds, and visual detail in the real world. Lack of fidelity at this stage can reduce the face validity of the simulation and create another source of time delay and noise injection into the system.

B. ANALYSIS OF MONITORING AND DECISION MAKING BEHAVIOR

Given the conceptual construct in Fig. 12 we can now consider various qualitative and quantitative methods for analyzing monitoring and decision making behavior. In general we are concerned with decisions made under risk involving the possibility of loss or injury. This implies some uncertainty in the consequences of a given decision/action, and this uncertainty is represented by the various noise sources in Fig. 12.

Qualitatively, the decision maker weights the various alternatives available to him, and picks the most desirable or least undesirable. The nature of this weighting process has been the subject of a large body of research, and has resulted in various decision making analysis approaches. Several of these are described below.

1. Risk Avoidance

This approach attempts to describe the avoidance or minimization of risk in situations consisting of many decision alternatives. The basic assumptions of the model, in addition to presuming that an alternative's risk increases with the mean of its probability of loss, is that risk is related to: 1) the variance of the outcomes; 2) the maximum loss or regret; and 3) the range of outcomes (Ref. 55). These various factors can be accounted for by weighting schemes as discussed below.

2. Linear and Functional Models

These models make a minimum of assumptions and can be considered as data analysis paradigms. The "linear model" generally defines the attractiveness, α, of a decision alternative, A_i, as a sum of weighted probabilities,

P_{ij}, plus weighted rewards (values), V_{ij}, plus a constant, i.e.,

$$\alpha(A_i) = \sum_j \left(W_{ij}P_{ij} + w_{ij}V_{ij} \right) + C_i \qquad (6)$$

where the W_{ij} and w_{ij} are the weightings. Regression analysis is generally used to determine the weights.

The "functional model" weights stimuli or pieces of information (S_{ij}) about the situation which have "scale values" as opposed to the axiomatic assumptions of probabilities or values in the models discussed below. The attractiveness, α, of an alternative, A_i, is

$$\alpha(A_i) = \sum_j W_{ij}S_{ij} \qquad (7)$$

Analysis of variance procedures are generally applied to the data. The results of application of these models is somewhat mixed (Ref. 55). Their main appeal is in the associated data analysis procedures (i.e., regression and analysis of variance) which are relatively straight-forward and readily available.

3. Expectation Maximization

The net value of multidimensional decision alternatives can be modeled as a sum of the probabilities of the various decision outcomes, each weighted according to the value of the outcome to the decision maker. The basic tenet of the theory is that a decision maker will select the alternative which maximizes the expected value. The model takes the following form, the notation depending on whether the probabilities and values are objective or subjective (i.e., perceived by the operator):

$$EV(A_i) = \sum_j P_{ij}V_{ij}(x_j) \qquad (8)$$

where

x_j	is a possible <u>outcome</u> or consequence of decision A_i (the x_j's are generally assumed to be a mutually exclusive and exhaustive set)
V_{ij} or (U_{ij})	is the <u>objective value</u> (or <u>subjective utility</u> of outcome x_j given decision A_i)
P_{ij} or (SP_{ij})	is a <u>conditional probability</u> (<u>subjective conditional probability</u>) of outcome x_j given decision A_i given the state of the environment (for x_j as above, it is generally assumed that $\sum_j P_{ij} = 1$).

For various combinations of objective and subjective probabilities and values different expectation functions can be defined:

$EV(A_i)$	Objective <u>Expected Value</u> for objective probabilities and values
$SEV(A_i)$	<u>Subjective Expected Value</u> for subjective probabilities and objective values
$EU(A_i)$	<u>Expected Utilities</u> for objective probabilities and subjective utilities
$SEU(A_i)$	<u>Subjective Expected Utility</u> for subjective probabilities and utilities

This model has been used to study the affects of alcohol on driver decisions at stop lights (Ref. 51). One key conclusion from this research was that driver perceptual variability increased under alcohol, which was the cause of increased risk taking. Fatigue, high workload, etc., might also lead to increased perceptual variability in an aircraft/ATC scenario, so this is a potential error source to consider.

4. Signal Detection Theory

Signal detection theory is a special application of the expected value theory above which has found considerable application in modeling the psychophysics of monitoring behavior and decision response. This theory has been applied to the lane change maneuver in driving (Ref. 52) and expanded for application to man-vehicle problems in general in Ref. 56. This theory postulates a decision maker's task as determining which of two hypotheses is true from one available observation. To make decisions in an optimal manner, Ref. 57 considers maximizing one among the following objectives:

(a) "Correct response" fraction

(b) Expected value

(c) Weighted differential probability ("correct response" minus "false alarm")

(d) A posteriori probability

(e) "Correct response" probability at fixed "false alarm" probability (commonly known as the Neyman-Pearson objective).

At any given signal-to-noise ratio, all of the objectives listed above yield the same strategy based on a likelihood ratio criterion (Ref. 58). Reference 56 shows, furthermore, that, for the objectives listed, the likelihood ratio criterion level remains constant as the signal-to-noise ratio is varied unless the Neyman-Pearson objective (e) is employed by the decision maker.

Consequently Ref. 56 proposes an interpretive model for decision behavior in which the observer is presumed to perform the optimal processing using subjective rather than objective probability distributions. (Bayes' rule is applied to subjectively perceived distributions.) One possible interpretation for the experimental results involves the use of a subjective Neyman-Pearson decision strategy; another possible interpretation implies breakdown of the subjective expected utility principle. One unequivocal

finding is that for experimental situations in which signal-to-noise ratio is allowed to vary from trial to trial, decisions are not made on the basis of a constant (objective) likelihood ratio criterion.

C. DECISION MAKING ANALYSIS EXAMPLE

The very terminal phase — from decision height on — of the aircraft landing example already described can be used to illustrate the various decision-making concepts discussed above, and their application to laboratory/simulation research. The example used here was adapted from earlier work (Ref. 59). First, the decision alternatives and related outcomes or consequences must be identified as summarized in Table 15. The outcomes also suggest associated performance measures that can be made in lieu of experiencing any of the rare event outcomes. This is important because of the extremely low accident probabilities in aircraft operation which would require an extremely large number of runs to obtain reliable occurrence rates. The sample distribution of the subsidiary performance measures so obtained can then be fitted with an appropriate distribution curve, and used to predict the probability of an accident (e.g., hard landing, run off runway, etc.).

Given the decision alternatives and outcomes, we next consider the conditional probabilities of success or accident given a "land" or "go around" decision. In Fig. 13 we have illustrated a probability tree model adapted from Ref. 59 that can be used to establish the conditional probabilities. The probability elements in Fig. 13 are assumed to be independent so that the product of the component probabilities along a path from the decision alternative to the outcome gives the conditional probability for the various outcome/alternative pairs. In Ref. 59 it is discussed how the various probability components depend on aircraft and wind gust characteristics.

The last step in analyzing or simulating the decision making aspects of the landing example is to establish values or utilities for the various outcomes. The pilot's subjective impression of the value structure is

TABLE 15

DECISION COMPONENTS SUMMARY FOR LANDING EXAMPLE

DECISION ALTER-NATIVE	BASIC OUTCOME		ASSOCIATED PERFORMANCE MEASURES
Land	Successful landing		Dispersions at decision height and/or reference position and at touchdown
	Accident	Short landing	Longitudinal touchdown location
		Hard landing	Sink rate at touchdown
		Overrun runway during rollout	Airspeed and altitude errors at reference position
		Land off side of runway	Lateral touchdown location
		Drag a wing tip or engine pod during landing	Bank angle at touchdown
		Land with excessive misalignment angle (putting side loads on landing gear)	Side velocity at touchdown
		Run off side of runway during rollout	Lateral displacement
Go Around	Successful abort and go around		Dispersions at decision height and range to other aircraft and obstacles
	Accident	Unsuccessful abort	Altitude, range to obstacles
		Unsuccessful go around	Range to other aircraft or obstacles, fuel level
		Unsuccessful approach	Range to other aircraft, fuel level

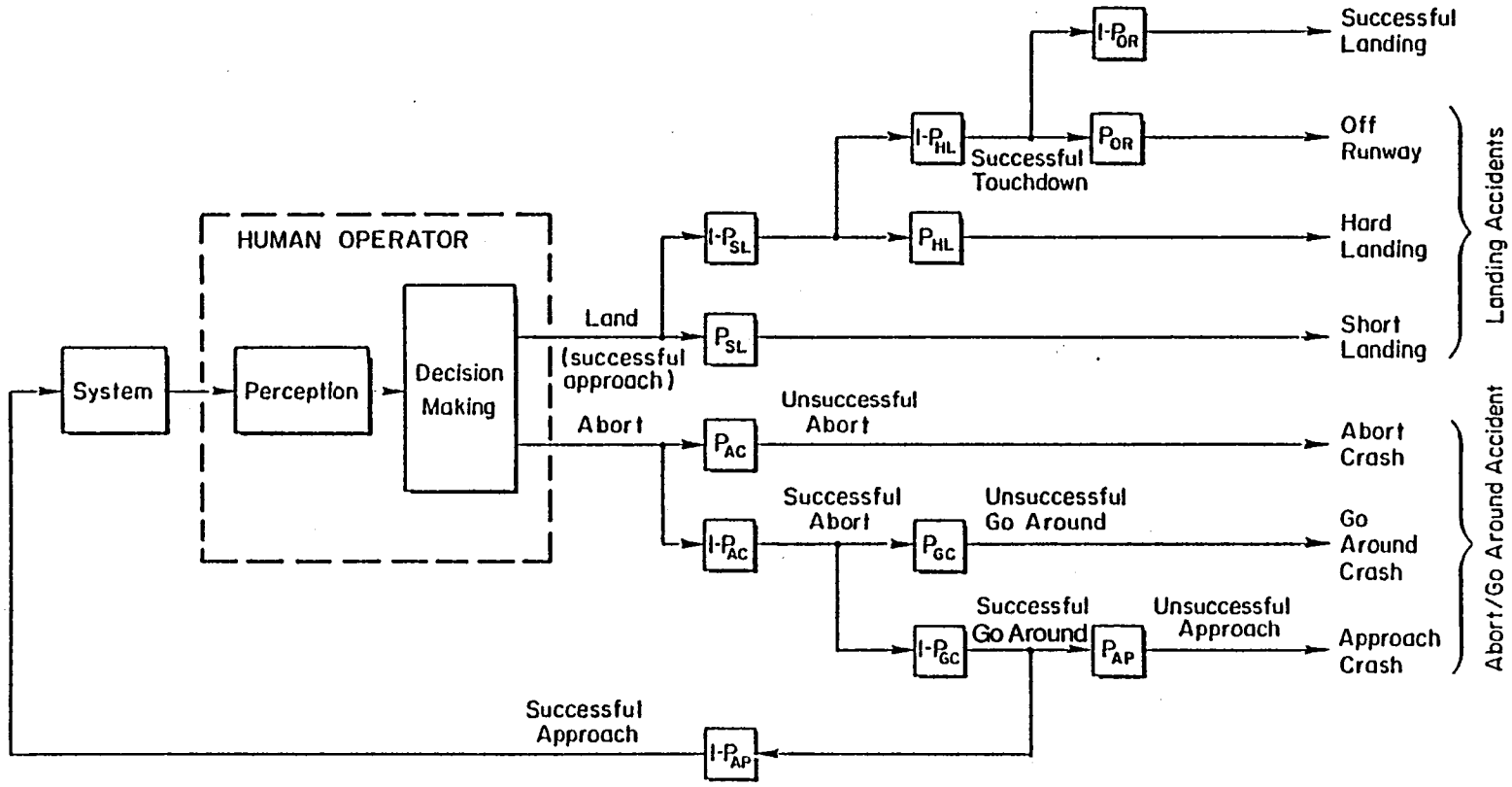

Figure 13. Landing Model Probability Tree for Determining Conditional Probabilities in Decision Making Expected Value Model

most pertinent, and application of utility theory (e.g., Ref. 60) might be helpful here in establishing the ranking and relative magnitude of the outcome value structure.

It should be noted that the landing example might also be considered as a sequential decision making situation where with each go around, fuel quantity diminishes, and the weather and aircraft condition may be degrading. Thus various conditional probabilities can change on successive go arounds.

SECTION VI

CONCLUSIONS

Human errors in aviation tend to be treated in terms of clinical and anecdotal descriptions, from which remedial measures are difficult to derive. Correction of the sources of human error requires that one attempt to reconstruct underlying and contributing causes of error from the circumstantial causes cited in official investigative reports. A comprehensive analytical theory of the cause-effect relationships governing propagation of human error is indispensable to a reconstruction of the underlying and contributing causes. This report presents a validated analytical theory of the input-output behavior of human operators involving manual control, communication, supervisory, and monitoring tasks which are relevant to aviation operations. This theory of behavior, both appropriate and inappropriate, provides an insightful basis for investigating, classifying and quantifying the needed cause-effect relationships governing propagation of human error. Highlights of the insight provided by this theory follow.

A. The input-output behavior of human operators in manual control systems is characterized by an internal organization involving three major pathways. These correspond to closed-loop, combined open- and closed-loop, and open-loop behavior patterns. In manual control systems which exemplify these patterns, the system bandwidths, attentional fields, and rehearsal requirements are ordered correspondingly, i.e., compensatory < pursuit < precognitive. Similar but inverted orderings of perceptual motor loading and system latencies are associated with the three pathways.

B. The three-pathway model for manual control can be generalized to a perceptually-centered model appropriate for input-output human behavior involving sensory modalities other than vision and output modalities other than manipulation.

C. The perceptually-centered model for human behavior is further generalized to include an executive and supervisory-monitoring metacontroller which identifies the situation, selects the appropriate pathway, directs the information flow

through the pathway selected, and monitors, on an off-line basis, the resulting outputs. The off-line monitoring feature constitutes yet another feedback, albeit on an intermittent and longer term basis.

D. The characterization of human behavior presented here provides a rational basis for planning specific investigations of the sources of human error using full mission simulation, either for the purpose of research in advance or diagnosis after the fact. When the purpose and scope of a simulation study has been set forth, the behavioral models summarized here can be used to predict (sometimes), subsume, describe, and rationalize the experimental results. For these tools to be most useful the experimental planning considerations should include the following activities.

1. Develop mission phase, task breakdown for nominal conditions. For each task, each crew member, and each traffic controller, list:

   a. An ordinal time line of activities.

   b. Input/output modalities for each task and nominal (unimpaired, highly trained) human operational mode (precognitive ≡ open loop, compensatory ≡ error correcting, pursuit ≡ combined open, closed loop, store ≡ to memory, for association).

   c. "Displayed" (perceivable from some source), controlled (attended to in control tasks), monitored variables.

   d. Command profiles, monitoring goals.

   e. Determine event markers and human operator input-ouput behavioral status (e.g., short term bandwidth) indicators; connect with the ordinal time line.

2. Define decision points within the mission phase/task structure.

   a. Break decision complex into sequences of binary choices.

   b. Develop a comprehensive list of outcomes (with which probabilities will be associated).

   c. Determine surrogate or connected measures for each outcome (from which sample measurements will be taken as the basis for a distribution fitting function).

3. Off-nominal and abnormal scenario elements

   a. Determine the off-nominal/abnormal mission phase shifts which are to be exercised to increase workload, divide attention, interrupt routine, impair human operations, etc. These should be selected to exercise the simulation subjects in roles likely to be crucial to the topics being focused on in the simulation.

   b. Expand the mission phase/task breakdown (and the outcomes in the decision complex, if needed) to account for the off-nominal scenario elements.

E. When the source and presence of grievous errors are to be recognized and quantified, the event identifiers/markers and human input-output behavior indicators of a given run with grievous errors present can

   1. Be compared with pre-determined error tolerances, and/or

   2. Be compared with a similar error free run.

   The results of these comparisons for the human input-output behavior indicators can be used to deduce the human error source and its correlates in any malfunctions of other subsystem or extreme inputs or disturbances. Similarly, the event markers and pertinent state variables will be the tip-off, and basis for quantification, of machine-centered error sources.

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16. Abstract

Human error is a significant contributing factor in a very high proportion of civil transport, general aviation, and rotorcraft accidents. Finding ways to reduce the number and severity of human errors would thus appear to offer promise for a significant improvement in aviation safety. Human errors in aviation tend to be treated in terms of clinical and anecdotal descriptions, however, from which remedial measures are difficult to derive. Correction of the sources of human error requires that one attempt to reconstruct underlying and contributing causes of error from the circumstantial causes cited in official investigative reports. A comprehensive analytical theory of the cause-effect relationships governing propagation of human error is indispensable to a reconstruction of the underlying and contributing causes. This report presents a validated analytical theory of the input-output behavior of human operators involving manual control, communication, supervisory, and monitoring tasks which are relevant to aviation operations. This theory of behavior, both appropriate and inappropriate, provides an insightful basis for investigating, classifying, and quantifying the needed cause-effect relationships governing propagation of human error.

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